REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1996

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
The Severe Weather Warning Process Using The WSR-88D At The Raleigh Weather Forecast Office

5. FUNDING NUMBERS

6. AUTHOR(S)
Debra Kay Hoium

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFIT Student Attending: University of North Carolina

8. PERFORMING ORGANIZATION REPORT NUMBER
96-039

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DEPARTMENT OF THE AIR FORCE
AFIT/CI
2950 P STEET, BLDG 125
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release IAW 190-1
Distribution Unlimited
BRIAN D. GAUTHIER, MSgt, USAF
Chief Administration

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

19960809 075

14. SUBJECT TERMS

15. NUMBER OF PAGES
108

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements***.

Block 1. Agency Use Only *(Leave blank)*.

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C	- Contract	**PR**	- Project
G	- Grant	**TA**	- Task
PE	- Program Element	**WU**	- Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

DOD - See DoDD 5230.24, "Distribution Statements on Technical Documents."
DOE - See authorities.
NASA - See Handbook NHB 2200.2.
NTIS - Leave blank.

Block 12b. Distribution Code.

DOD - Leave blank.
DOE - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
NASA - Leave blank.
NTIS - Leave blank.

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code *(NTIS only)*.

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

★U.S.GPO:1990-0-273-271

ABSTRACT

HOIUM, DEBRA KAY. The Severe Weather Warning Process using the WSR-88D at the Raleigh Weather Forecast Office. (Under the direction of Allen J. Riordan.)

For over a century, meteorologists have been attempting to improve severe thunderstorm and tornado forecasts. In recent years, the Doppler radar was developed in an attempt to increase severe weather warning timeliness and accuracy. This research is a preliminary analysis of the severe weather warning process using the WSR-88D at the Raleigh Weather Forecast Office (RDU WFO).

A schematic representation of the warning process was developed based on 68 thoroughly documented warnings during 1995. A flow-chart has been developed to describe the decision making process. Most warnings have an initiator followed by a trigger. The initiator causes the radar operator to consider the issuance of a warning and marks a period of intensive cell investigation. A final event, termed the trigger, leads to the decision to issue the warning. The trigger for severe thunderstorm warnings is most frequently a reflectivity based Doppler radar product while for tornado warnings Doppler velocity products are most commonly utilized. Ground truth reports are still important in the Doppler radar era especially for the decisions not to issue warnings and quick decisions to issue warnings, called immediate trigger warnings. After the warning is issued, 85 percent of the warned counties are called leading to the verification of 38 percent of the warnings during the severe weather episode. Seventy percent of these severe weather reports are accurate if *Storm Data* is used as the ground truth.

The probability of detection (POD) at the RDU WFO has statistically significantly improved since operational use of the WSR-88D began in March of 1994. However, as of November 1995 both the false alarm rate (FAR) and critical success index (CSI) have gotten worse with the use of the Doppler radar. It has further been found that the FAR has increased from 1994 to 1995. The hypothesis for such increases in the FAR is that there is a tendency to over warn until the forecaster gains operational experience on the WSR-88D. More forecasters were having their first operational experiences with the Doppler radar during 1995 than 1994. Placing the warnings in categories revealed that the POD is higher during periods with severe thunderstorm or tornado watches as well as for severe weather episodes with more than four warnings. Finally, the population density and per capita income do not have a statistically significant impact on either the verification rate or the number of warnings issued.

THE SEVERE WEATHER WARNING PROCESS USING THE WSR-88D AT THE RALEIGH WEATHER FORECAST OFFICE

by

DEBRA KAY HOIUM

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Marine, Earth and Atmospheric Sciences

Raleigh

1996

APPROVED BY:

Chair of Advisory Committee

BIOGRAPHY

Lieutenant Debra Kay Hoium [redacted] She attended high school at Columbia Heights High School in suburban Minneapolis and graduated in June of 1990. It was during high school that her only sibling, Betsy, taught her everything she knows about writing.

Lt. Hoium then attended the United States Air Force Academy in Colorado Springs, CO. On 01 June 1994, she was a distinguished graduate from the Academy with a bachelor of science in mathematics and was commissioned as a second lieutenant in the United States Air Force. Lt. Hoium was selected for the weather career field.

In the fall of 1994, Debra was admitted into the Air Force Institute of Technology and was sent to North Carolina State University to pursue her master's degree in meteorology.

"episodes" will refer to the time periods when warnings are issued with a maximum of

ACKNOWLEDGMENTS

I would like to thank the United States Air Force for funding my education and providing me the opportunity to pursue my master's degree in meteorology through the Air Force Institute of Technology. This research was also supported by NOAA through the Southeast Consortium on Severe Thunderstorms and Tornadoes.

My advisor, Dr. Allen J. Riordan, deserves much credit for this research. He has spent countless hours encouraging me and focusing my research. Dr. Riordan is also responsible for organizing the North Carolina State University participants in the collaboration with the Raleigh Weather Forecast Office which made this research possible. He has also put in hundreds of hours participating in almost all of the collaborative severe weather episodes.

I would also like to thank the other members of my committee, Dr. John F. Monahan and Dr. Jerry M. Davis, for their statistical advice and support of this research. Kermit K. Keeter, the Scientific Operations Officer at the RDU WFO, has provided much assistance for my research as well as coordinated the collaboration. Also from the RDU WFO, George Lemons and Gail Hartfield-Supina provided me with the severe weather folders and the radar images used in this thesis. In addition, I would like to thank all the forecasters at the RDU WFO for their support of the collaboration. Further, credit is due to Don Burgess of the Operational Support Facility and John T. Halmstad of the Storm Prediction Center for providing me background information.

Finally, the following students deserve credit for helping me both with this research and with my course work: Lisa Hagerman, Adam Langmaid, Jim O'Conner, Paul Roelle, Bob Rozumalski, and Bob Trayers.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

CSI:	Critical Success Index
FAR:	False Alarm Rate
JDOP:	Joint Doppler Operational Program
MAR:	Modernization and Associated Restructuring
NCSU:	North Carolina State University
NSSFC:	National Severe Storms Forecast Center
NSSL:	National Sever Storms Lab
NWS:	National Weather Service
OKC:	Oklahoma City
PDS:	Process Data Set
POD:	Probability of Detection
PUP:	Principal User Processor
RDU:	Raleigh Durham
RWA:	Raleigh Warning Area
SDS:	Statistical Data Set
SPC:	Storm Prediction Center
SWAT:	Severe Weather Action Team
SWATR:	Severe Weather Action Team Reports
SVR:	Severe Thunderstorm Warning
TOR:	Tornado Warning
VIL:	Vertically Integrated Liquid

WFO: Weather Forecast Office

WSR-57: Weather Surveillance Radar-1957

WSR-88D: Weather Surveillance Radar-1988 Doppler

1. INTRODUCTION

"In a typical year, the United States can expect a staggering assault by the elements: some 10,000 violent thunderstorms, 500 floods, 1000 tornadoes, and several hurricanes" (Friday, 1994). Clearly, this situation emphasizes the importance of timely and accurate severe weather warnings to protect the American public. However, the first weather warnings were issued only a century and a half ago.

1.1 The First Severe Weather Warnings

Professor Joseph Henry, secretary of the Smithsonian Institution, devised the first weather warning system in the United States in 1849 using a telegraph network and 150 volunteers (Hughes, 1970). His system grew to include over 500 stations by 1860, but the Civil War caused reductions thereafter (Whitnah, 1961).

The modern severe thunderstorm and tornado watch procedures were developed with the advent of the National Severe Storms Forecast Center (NSSFC) in 1953 (The Tornado Project, 1994). Possibly as a result, 1953 was the last year that a single tornado killed over 100 people (The Tornado Project, 1994). Severe weather warnings were developed soon after the first watches. While both watch and warning procedures have been refined, the basic system is still used today and will be presented in the following section.

1.2 Verification Techniques

From the earliest forecasts, meteorologists have been interested in assessing their performance. John P. Finley devised the first verification scheme for his tornado

predictions in the 1880's (Flueck, 1987). Finley expressed a view which is still considered valid today, "...it requires as much, and often more, study to say that no tornadoes will occur as to make the prediction that conditions are favorable for their development" (Galway, 1985 quoting Finley, 1884). To incorporate accurate forecasts for non-tornadic events, Finley considered a verified forecast as any correctly identified tornado or no tornado period (Flueck, 1987). Using this method, Finley's verification scores ranged from 96 to 99 percent (Flueck, 1987). However, if Finley had never predicted a tornado, his verification rate would have been 98 percent (Flueck, 1987). Clearly, there was a problem with Finley's verification scheme and the debate for the proper method of analyzing forecast skill and accuracy continues today.

Current severe weather warning and verification procedures are defined by the National Severe Storms Forecast Center (NSSFC), now called the Storm Prediction Center (SPC), in Kansas City, MO (Crowther and Halmstad, 1994) and will be used in this report. The NSSFC's definition of a "severe local storm event" is any tornado or wind gust in excess of 50 knots or thunderstorm wind damage or hail with a diameter 3/4 inch or greater (Grenier and Halmstad, 1986). Multiple reports of severe local storm events that occur within the same county are recorded as one event if the reports are within ten square miles and fifteen minutes of each other (Crowther and Halmstad, 1995). As an exception to this rule, the following cases are always treated as individual severe local storm events:

1) all distinct tornadoes

2) wind gusts in excess of 65 knots and hail with a diameter greater than two inches, and

3) all events with reported fatalities, injuries, or more than half a million dollars worth of damage (Crowther and Halmstad, 1995).

In this report, severe local storm events will be referred to as severe weather events or simply events.

Severe thunderstorm and tornado watches are issued by the NSSFC for areas where severe local storm events are forecast to occur (Crowther and Halmstad, 1993). These watches usually include areas of roughly 50,000 square kilometers and are typically valid for up to six hours.

In contrast, the local Weather Forecast Offices (WFO) of the National Weather Service (NWS) issue warnings to "alert the public to an imminent or existing severe thunderstorm or tornado" (Crowther and Halmstad, 1995). Severe thunderstorm and tornado warnings are issued for all or part of a county and are generally valid for less than one hour. Each WFO issues warning to their defined area of responsibility. Appendix 7.1 shows the Raleigh Warning Area (RWA).

The local WFO then uses phone calls, ham radio reports, damage surveys and newspaper articles to compile a list of all events in their region. The reports of all WFO's are compiled in *Storm Data: A Composite of Outstanding Storms* which then becomes the official verification source. This research uses the July and August, 1994 editions of *Storm Data* as well as press-ready versions of the North Carolina entries for June of 1994 and all of 1995 (Lemons, 1995).

A warning verifies if there is a report in *Storm Data* of an event within the warned county and during the valid warning period (Crowther and Halmstad, 1995). Any severe

local storm event verifies either a severe thunderstorm or a tornado warning (Crowther and Halmstad, 1995). This is clearly a generous verification procedure since for successful warnings, the type of warning and type of severe event do not have to match. For example, a wind gust in excess of 50 knots verifies a tornado warning. Since warnings are issued by county, verification is also done by county. This means that if a warning is issued for two counties, each warned county is treated individually for verification purposes (Crowther and Halmstad, 1995).

The verification results are then used to compute the verification statistics. Three of the most common verification statistics used today are the probability of detection (POD), the false alarm rate (FAR) and the critical success index (CSI). First, there are four basic variables involved in verification statistics as shown in Table 1.1.

Table 1.1. Contingency table showing variables involved in verification statistics (Schaefer, 1990).

		FORECASTS	
		Yes	No
EVENTS	Yes	X	Y
	No	Z	W

The number of correct forecasts for severe local storm events and non-severe local storm events are X and W respectively, while the total number of unverified positive and negative forecasts are Z and Y. While researchers agree that W should not be ignored, there is not a standard way to deal with the infinite number of correct decisions not to warn a county. In the remainder of this report, "misses" will be defined as Y and

"episodes" will refer to the time periods when warnings are issued with a maximum of three hours between warnings. Notice also that the number of events is X + Y.

Now the verification statistics can be defined. The probability of detection is defined as:

$$POD = \frac{X}{X+Y} \qquad \text{(Schaefer, 1990)}$$

and is simply the percentage of events for which a warning has been issued (Schaefer, 1990). A perfect POD is 1.00. The false alarm rate is a measure of the failure to exclude non-severe events and is defined as:

$$FAR = \frac{Z}{X+Z} \qquad \text{(Schaefer, 1990)}$$

and should be minimized. Both the POD and FAR are easy to understand statistics, but they do not account for all available information (Flueck, 1987). The POD would be very high if warnings were issued everyday. The FAR would be very low if warnings were not issued for marginal cases.

A statistic that includes X, Y, and Z is the critical success index:

$$CSI = \frac{X}{X+Y+Z} \qquad \text{(Schaefer, 1990).}$$

The CSI combines information from both the POD and FAR as shown in the following representation:

$$CSI = \left[\frac{1}{POD} + \frac{1}{1-FAR} - 1\right]^{-1} \qquad \text{(Grenier \& Halmstad, 1988).}$$

Like the POD, a perfect CSI is 1.00. There are still several problems with the CSI, however. It does not account for correct negative forecasts, 'W' from the previous table (Flueck, 1987). Also, it is biased toward areas with many events (Schaefer, 1990).

A problem with using verification statistics as the only indicator of performance is that the WFO's often rely on non-meteorological factors to improve their scores (Hales and Kelly, 1985). The forecaster is tempted to focus on the probability of obtaining verification when deciding whether to issue a warnings to a given county (Hales and Kelly, 1985). For example, national data from 1979 to 1983 showed significantly more warnings were being issued for highly populated counties (Hales and Kelly, 1985).

A second approach toward improvement is implementing a more aggressive search for ground truth reports to verify warnings (Hales and Kelly, 1985). In 1983, the Oklahoma City (OKC) WFO began an extensive post storm survey report and Table 1.2 shows the effects it had on their verification statistics (Hales, 1988).

Table 1.2. Verification Statistics for the OKC WFO illustrating the effects of increased efforts at gaining ground truth reports in 1983 (Hales, 1988).

Year	Events Reported	Counties Warned	POD	FAR	CSI
1982	258	563	0.508	0.801	0.167
1983	499	551	0.729	0.508	0.416
1984	509	568	0.786	0.423	0.499
1985	558	543	0.774	0.346	0.549
1986	902	763	0.822	0.287	0.617

The number of events reported increased four fold and the FAR decreased from .801 to .287 in the four year test period. The problem with this method of improving verification

statistics is that there is not enough time or personnel to compile a flawless list of severe weather events. Hales and Kelly (1985) conclude by pointing out that the emphasis perhaps should be placed on the rationale for issuing warnings rather than obtaining verification.

> In the public's perception a warning quite likely is justified if they experience intense lightning, heavy rainfall or even wind driven small hail. . . There is certainly a question at the present time whether the public's and the forecaster's best interests are being served as the [verification] program is now structured (Hale and Kelly, 1985).

With some of these limitations in mind, this thesis will analyze verification statistics for the Raleigh (RDU) WFO as well as the rationale and process of issuing warnings.

1.3 Preliminary Analysis of Doppler Radar Capabilities

An external method of improving verification statistics is through technological advances. The Doppler radar was developed in hopes of providing forecasters with improved warning capabilities. The first field experiment to test the operational use of the Doppler radar, the Joint Doppler Operational Project (JDOP), was conducted from 1976-78. This project was a combined effort of the National Severe Storms Laboratory (NSSL), the National Weather Service (NWS), the Air Weather Service, the Air Force Geophysical Laboratory and the Federal Aviation Administration (Burgess and Devore 1979).

According to the Final Report on JDOP: 1976-1978, operational tests showed the "marked improvement Doppler radar offers for early accurate identification of thunderstorm hazards, especially tornadoes and squall lines". The report goes on to

conclude that key advantages of the Doppler radar are: a reduced FAR, an enhanced POD and a decreased dependence on the "often erroneous" ground truth reports (Staff of JDOP, 1979).

These conclusions were based on a comparison between the verification statistics for warnings issued by the OKC WFO and advisories issued by the JDOP forecasters. The advisories were based solely on the Doppler radar with no public reports available to the forecaster. The warnings issued by the OKC WFO were based on ground truth reports, the WSR-57, and the Doppler advisories issued by the JDOP staff (Burgess & Devore 1979). Verification information was collected through records of telephone calls and newspaper clippings as is normally done. However, there was also an extremely in-depth quest for ground truth using numerous follow-up calls, the NSSL mesonetwork and the hail reporting network (Staff of JDOP, 1979). According to the Final Report on JDOP, "Participants believe that the 1977 and 1978 data make up probably the most complete verification list ever documented for severe storms" (Staff of JDOP, 1979). This enhanced reporting network increased the number of documented severe thunderstorms and tornadoes which would generally boost the verification statistics. Table 1.3 shows the breakdown of the number of warnings and advisories issued during the JDOP and the corresponding verification statistics. The Doppler advisories consistently improved the FAR and CSI. The last category, 1978 tornadoes, is the only circumstance where the POD dropped for the Doppler advisories. This can be explained by the extremely high FAR and greater number of warnings issued by the OKC NWSO.

Table 1.3. JDOP Verification Statistics (Staff of JDOP, 1979)

1977 SEVERE STORMS & TORNADOES		
	OKC NWSO	Doppler Advisories
Number	115	23
POD	0.58	0.75
FAR	0.54	0.22
CSI	0.34	0.62

1978 SEVERE STORMS		
	OKC NWSO	Doppler Advisories
Number	70	56
POD	0.47	0.7
FAR	0.4	0.16
CSI	0.36	0.62

1978 TORNADOES		
	OKC NWSO	Doppler Advisories
Number	42	7
POD	0.75	0.56
FAR	0.79	0.38
CSI	0.2	0.42

Lastly, JDOP considered the justification for warnings. The forecasters at the OKC WFO were asked to provide reasons for issuing warnings. The results were tabulated giving equal weight to each response listed. Table 1.4 is taken from the Final report on JDOP and shows the relative frequencies of each justification. Note that all radar justifications are based on the WSR-57 except for the category "Doppler Radar" which came directly form a JDOP advisory. The OKC WFO did not have direct access to Doppler data (Staff of JDOP, 1979).

Table 1.4. Justification for issuing warnings during JDOP (Staff of JDOP, 1979)

Severe Thunderstorm Warnings		
Reason	**Issued**	**Verified**
1. Radar Reflectivities	43	20
2. Radar Tops	24	14
3. Reflectivity & Tops	38	19
4. Public Reports	19	11
5. Doppler Radar	16	10

Tornado Warnings		
Reason	**Issued**	**Verified**
1. Public Reports	37	17
2. Radar (hook echo)	27	5
3. Doppler Radar	23	10

The success of JDOP prompted a decade of development and production considerations resulting in the Weather Surveillance Radar-1988 Doppler (WSR-88D) (Alberty and Crum, 1991). The first operational WSR-88D was in Norman, OK in March of 1991 (Polger *et. al.* 1994). In 1991 and 1992, an operational analysis was done using six stations equipped with the WSR-88D resulting in "dramatic, consistent, and unprecedented improvements in the accuracies of warning service and lead time" (Friday, 1994).

1.4 The Modern National Weather Service Office

Installing the WSR-88D at 136 WFO's is a key component of the NWS's program called the modernization and associated restructuring (MAR) aimed at improving severe weather warning accuracy and timeliness (Polger *et. al.*, 1994 and Klazura and Imy, 1993). Unfortunately, the MAR has yielded less significant enhancement of mesoscale forecast performance than anticipated (Friday, 1994).

It may just take some time for dramatic improvements in forecast capability. The WSR-88D is a complex radar and requires both training and experience to master (Friday, 1994). The forecaster must be able to "manage effectively the 'avalanche' of data" because of the "myriad number of options" available on the WSR-88D (Lemon *et. al.*, 1992). Figure 1.1 illustrates the complexity of the warning process using the WSR-88D.

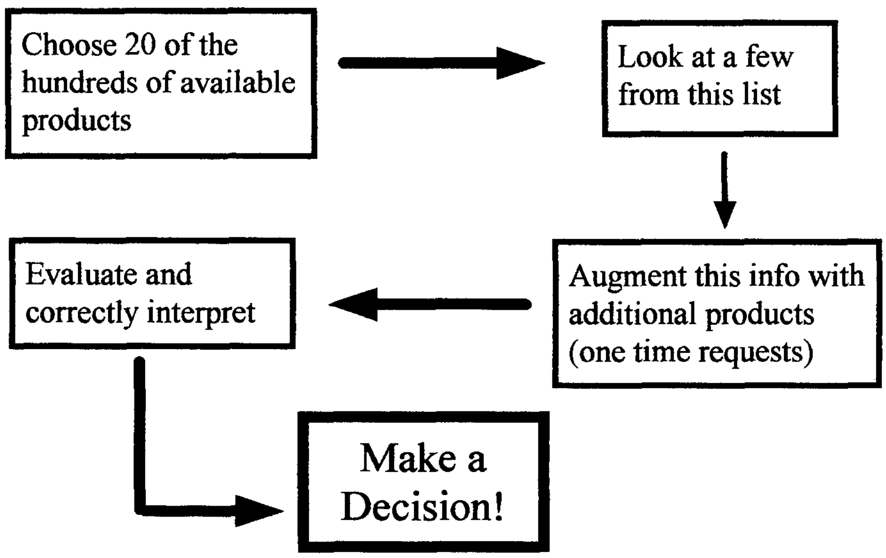


Figure 1.1. The warning process using the WSR-88D (Lemon *et. al.*, 1992).

1.5 Raleigh WFO and NCSU Collaboration

Another part of the MAR of the NWS is an emphasis on bringing the operational and research communities together. The NWS had established eleven collaborative relationships between forecast offices and universities (Auciello & Lavoie, 1993).

> The broad goal of collaborative research activities between National Weather Service (NWS) operational offices and universities is to advance the understanding of meteorological and hydrological phenomena and to use this understanding to enhance weather warnings, forecasts, and other weather services to the nation (Auciello & Lavoie, 1993).

It should first be pointed out that the atmospheric science program from North Carolina State University (NCSU) and the RDU WFO have been involved in collaborative research for several years. There have been 11 collaborative publications since 1992 on topics ranging from winter precipitation types to severe weather outbreaks. In addition, a number of forecasting techniques have been developed through the collaboration including: predicting water levels in the sounds of North Carolina, using sea surface temperatures to forecast the deepening rates of coastal storms, and predicting violent tornado outbreaks in the southeastern United States using a severe weather paradigm.

On a more operational level, NCSU faculty and students have formed the Severe Weather Action Team (SWAT) which has worked under the direction of the WFO during fifty severe weather events over the past three years. The purpose of the SWAT has been both to document and facilitate in the severe weather warning process. As a result, both researchers and forecasters are obtaining a model of how the warning process unfolds in real time. While the benefits of this program cannot be objectively measured, it has both provided support for the forecasters and given researchers insight into the warning process. Also, the experiences of the SWAT have channeled researchers toward practical forecast problems and initiated data collection for future research.

In order to understand how the SWAT operates, the chain of command for the RDU WFO must first be presented. Two of the key staff positions during severe weather operations are the storm coordinator and the radar operator. The storm coordinator has the ultimate warning responsibility. However, the radar operator generally recommends that a warning should be issued and the storm coordinator normally concurs. During collaborative events, members of the SWAT work under the direction of the storm coordinator. Three of the tasks performed by the SWAT members are: performing mesoscale analyses, initiating phone calls requesting ground truth and documenting the severe weather warning process from the perspective of the radar operator. Prior to the WSR-88D, the primary role of the SWAT was operational support. However, currently the team provides both assistance to the forecaster as well as documentation of the warning process. It is this documentation done by the SWAT since the RDU WFO began operational use of the WSR-88D in March of 1994 that has made this research possible.

1.6 Research Objectives

Thousands of severe weather warnings are issued in the United States each year, over a hundred of which originate from the RDU WFO. Each of these warnings is surrounded by a unique set of circumstances influenced by the meteorological characteristics, the accuracy and timeliness of ground truth reports, and the forecasters on duty. Each forecaster often only works during a few severe weather episodes each year and is unaware of how the warning process unfolds when he or she was not working.

Therefore, the objective of this research is to analyze how warnings are issued at the RDU WFO.

In order to attain this objective, the research has been divided into three phases.

1) Chapter two covers the data organization phase. First, details on the data sets utilized in this research will be provided. Then two case studies of severe weather episodes will be given to illustrate how the warning process unfolds in real time. These case studies will also serve as examples of the documentation done by the SWAT.

2) Then chapter three will then move to a more general view of severe weather operations through a schematic representation of the warning process.

3) Finally, a thorough discussion of the verification statistics is given in chapter four.

2. DATA ORGANIZATION

The data for this study come from four sources: the Warning Logs, Action Logs, SWAT reports, and *Storm Data*. The Warning Log is the WFO's listing of all warnings issued during an episode including the counties warned, the type of warning issued, and the time it was issued and expired. For this research, only severe thunderstorm (SVR) and tornado (TOR) warnings will be considered. The Action Log is the NWS's hand written record of the initiated and received phone calls in conjunction with the episode. The SWAT reports (SWATR) are the documented timelines of the activity during severe weather episodes from the perspective of the WSR-88D operator. Finally, *Storm Data* is used to verify warnings as discussed in the first chapter. The spreadsheet organization used in this research is provided in Appendix 7.2 and some excerpts from the spreadsheets are given in Appendix 7.3. This chapter first describes the data set for each phase of the analysis and then provides two case studies as real time illustrations of the warning process and examples of the SWATR.

2.1 The Data Set for Each Phase of the Analysis

There are two data sets in this research based on the information available: the Process Data Set (PDS) and Statistical Data Set (SDS).

The SWATR are the primary data source for the analysis of the warning process which includes information on the rationale behind issuing warnings. The SWATR contain detailed documentation of the sequence of events during the severe weather episode. However, when the WSR-88D was first used at the RDU WFO, the SWAT

recorders were not familiar with the products available on the new radar, and therefore the documentation was less complete. In light of this problem, the data set for the process section of this research has been limited to the 1995 SWATR, the second severe weather season with the WSR-88D.

Additional inconsistencies in the SWATR caused the process data set to be reduced further. Each SWAT recorder focused on different elements of the warning process. Also, some radar operators verbalized their thought process simplifying the documentation procedure, while it was more difficult to capture the decision making process for other operators. Finally, the SWAT recorder had a difficult time keeping up with the documentation during very active episodes. Therefore, the warnings logged in the 1995 SWATR had to be screened and only the thoroughly documented warnings have been included in the PDS. Also because the PDS will be used for the analysis of the warning process, multiple warnings issued to neighboring counties are treated as individual warning entries. The resulting PDS includes a total of 18 episodes encompassing 48 severe thunderstorm and 20 tornado warnings. This is over 90 percent of the 1995 warnings with SWATR and 33 percent of the total warnings issued by the RDU WFO in 1995. Figure 2.1 shows the severe weather episodes included in the PDS. Each asterisks represents a warning in the PDS while the lines indicate additional warnings that were not included in the PDS. Notice that the PDS includes several episodes with numerous warnings as well as six cases where less than four warnings were issued.

The Events in the Process Data Set (PDS)

Time (local--EST or EDT as applicable)

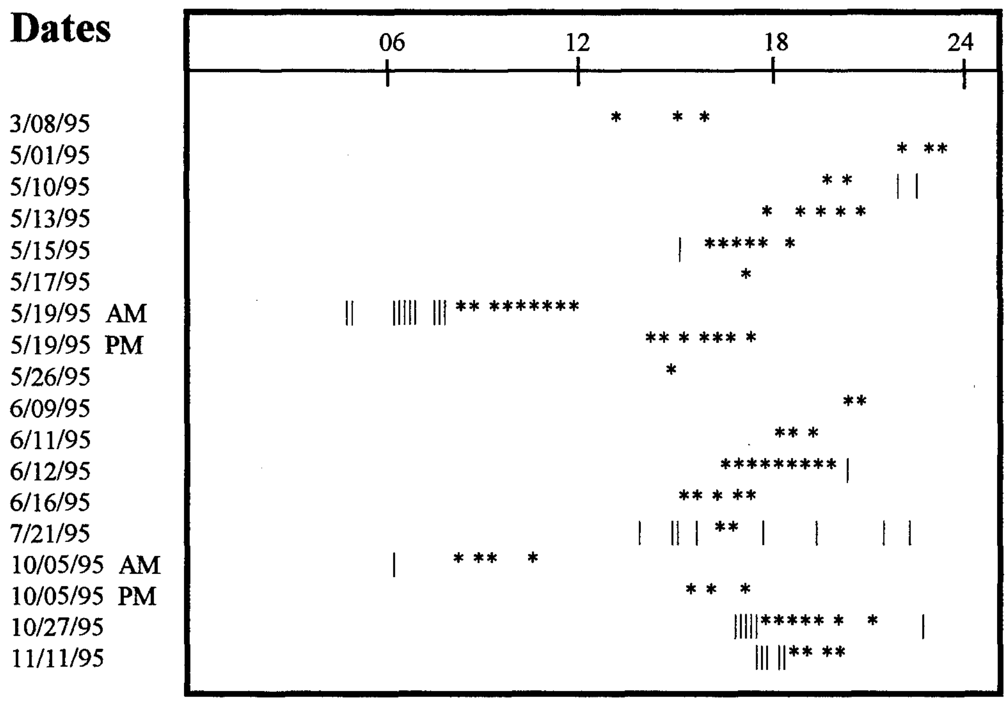


Figure 2.1. Pictorial representation of the PDS. The warnings in the PDS are indicated by the asterisks while the lines represent additional warnings during the severe weather episode.

For the analysis that does not require SWATR, the Statistical Data Set (SDS) was introduced. This data set includes information from the Warning Log, Action Log, and *Storm Data* and was useful in analyzing the verification statistics and importance of ground truth reports. The SDS is composed of the PDS as well as any additional warnings issued by the RDU WFO during the severe weather season after the WSR-88D was operational. This includes episodes from June through August of 1994 and from May through August of 1995. A total of 327 severe thunderstorm warnings and 24 tornado warnings are in the SDS.

2.2 Case Studies

In order to illustrate the type of information available in the PDS as well as give the reader an idea of how the warning process progresses in real time, two case studies have been included. The bracketed information in the cases relates to the warning process which will be presented in chapter three. The reader is encouraged to read through the cases first to get an overall idea of the activity at the WSR-88D Principal User Processor (PUP) during a severe weather episode. Then he or she should refer back to the cases while reading chapter three to see how these specific examples fit into the general model of the warning process.

The detailed summaries of the environment leading to the episodes come directly from the SWATR. The radar images have been included to show a few of the WSR-88D products utilized and to give the reader a better concept of the warning process from the perspective of the WSR-88D operator.

The first case is taken from October 5, 1995 and will illustrate the progression of events during a slow paced case where a cell develops, crosses through two counties and then dissipates. At 0900 UTC, a severe thunderstorm watch was issued for much of southern North Carolina. On the synoptic scale, there is warm moist air over North Carolina associated with the remnants of Hurricane Opal as shown on the surface analysis given in Figure 2.2. Notice the cyclone center is over eastern Tennessee and is tracking northward. Also, the surface dew points are in the mid 70's^{o} F across much of the region. A warm front has moved northwest during the night placing the RWA in

tropical air. The 1200 UTC (7:00 AM EST) Greensboro sounding given in Figure 2.3 is nearly moist adiabatic but there is strong veering of the winds with height in the lowest levels of the atmosphere. Thus, the helicity is high in the lowest layers. Based on a surface parcel of $T = 25°C$ and $T_d = 24°C$, the lifted index is -3 and the CAPE is 933 J/kg.

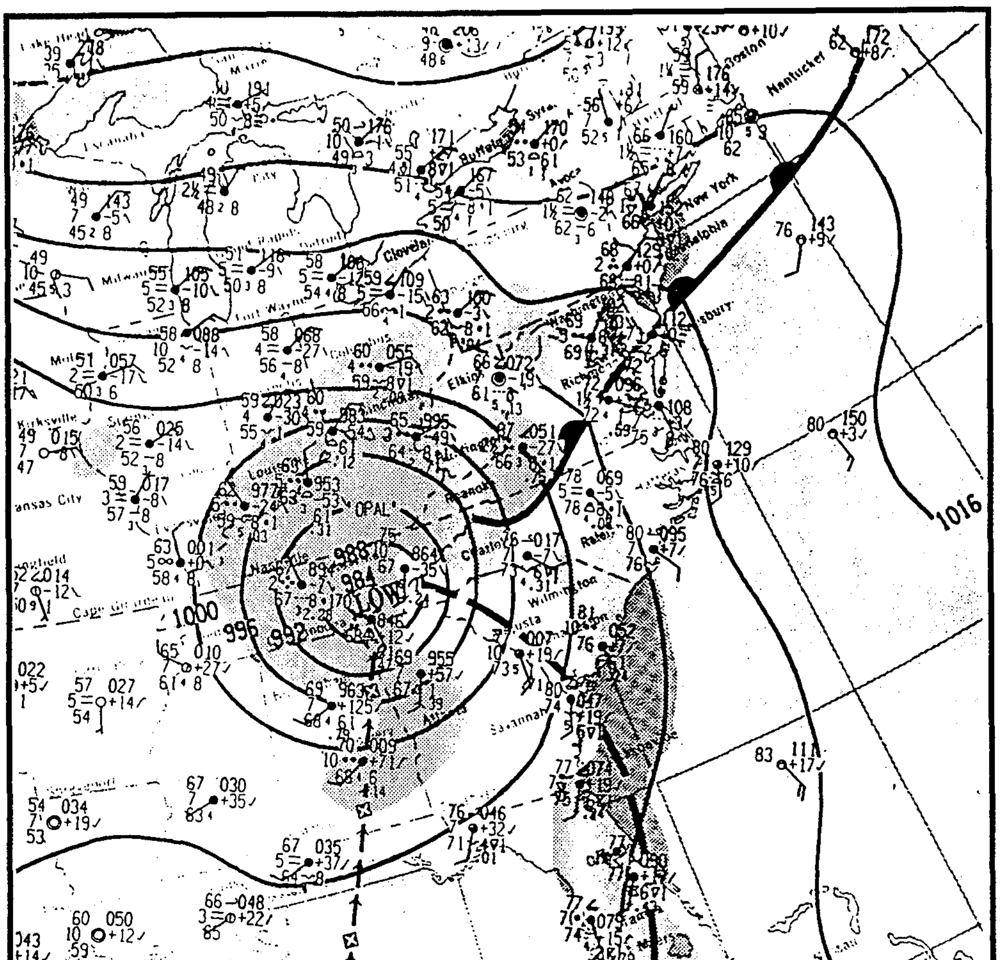


Figure 2.2. Surface Analysis for 1200 UTC 05 Oct. 1995 (Daily Weather Maps).

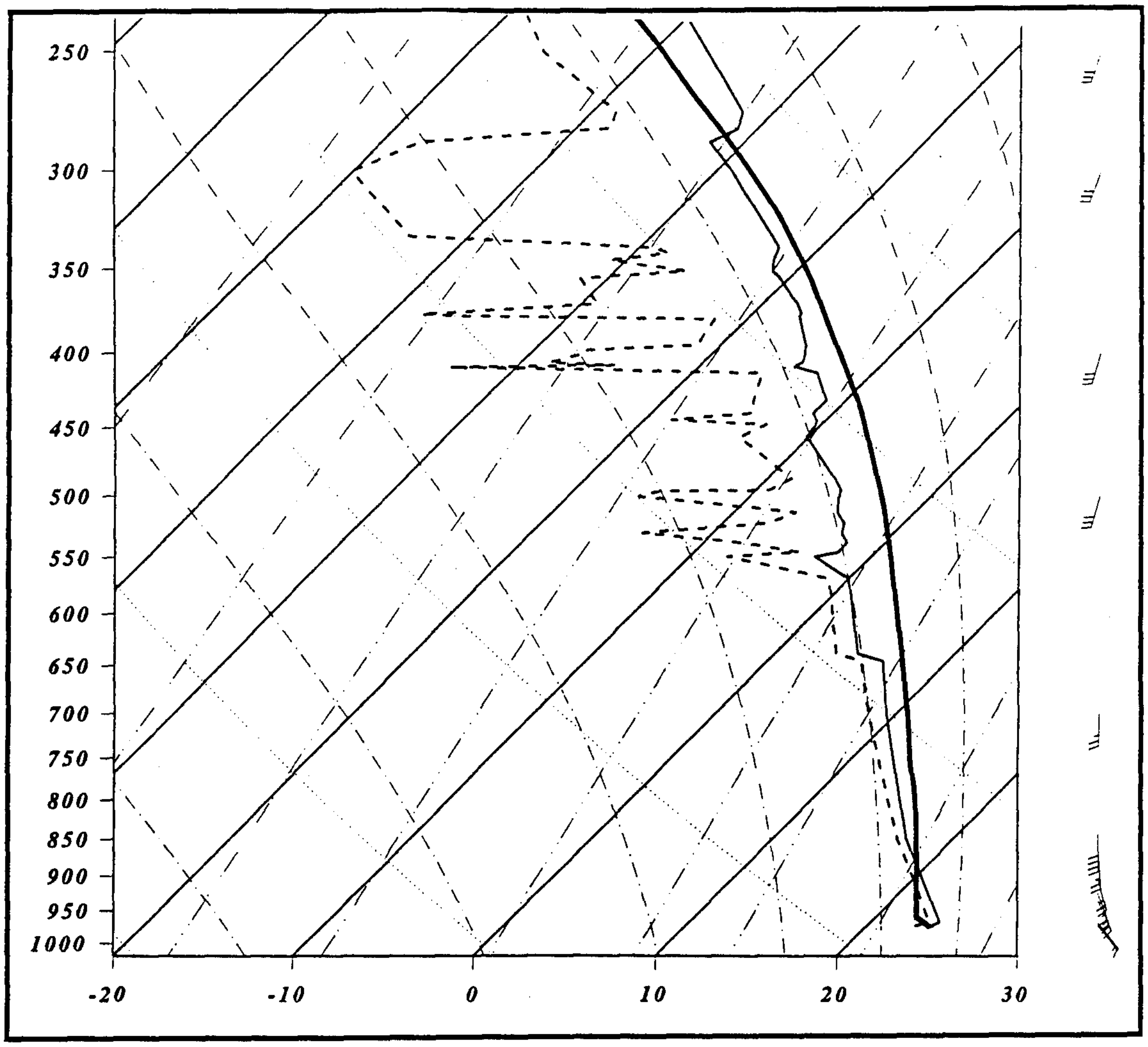


Figure 2.3. 1200 UTC 05 Oct. 1995 skew T-log *p* plot of Greensboro, NC (GSO). The dashed line is the dew point, the thin solid line is the temperature and the bold line represents the parcels path.

At about 07:00 AM EST, thunderstorms with tornadic potential are moving into the RWA from the south. Figure 2.4 shows the locations mentioned in the text. The times are given in EST. Tornado warnings are issued for Anson and Cumberland Counties prior to the SWATR segment that will now be presented.

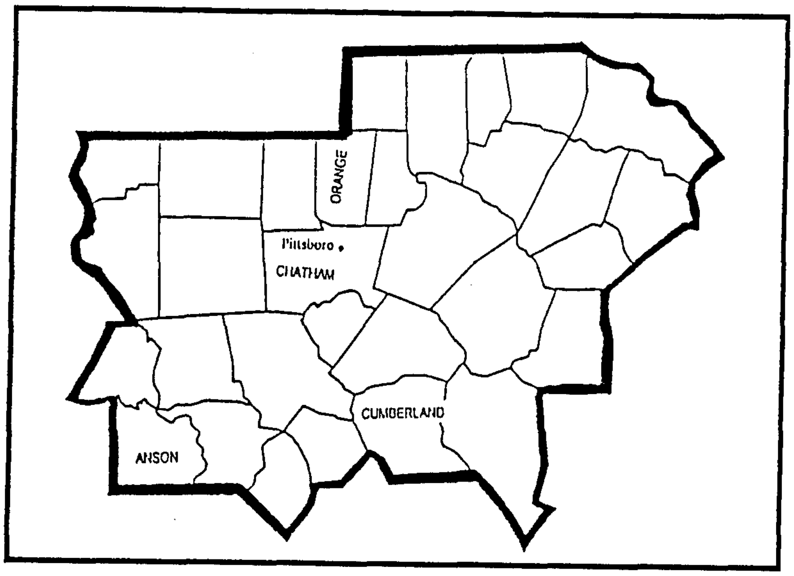


Figure 2.4. Location map for the 05 Oct. 1995 case.

08:29 The radar operator is looking at the relative velocity over central Chatham County. The gate-to-gate shear is 26 knots at 7,700 ft. [Initiator]

08:36 The shear is now 25 knots for the above cell. The four panel relative velocity and reflectivity products for 1230 UTC have been included as Figs. 2.5 and 2.6. The radar operators attention is focused on cell A in central Chatham County which is labeled at the 1.5 degree elevation angle in figures 2.5 and 2.6. Notice that the relative velocity for cell A indicates 35 knots of gate-to-gate shear at mid levels. The shear in Chatham County is well defined at both the 0.5 and 1.5 degree elevation angles. [Trigger] The radar is located to the southeast of each velocity panel as shown in Appendix 7.1. Figure 2.6 shows a reflectivity maximum

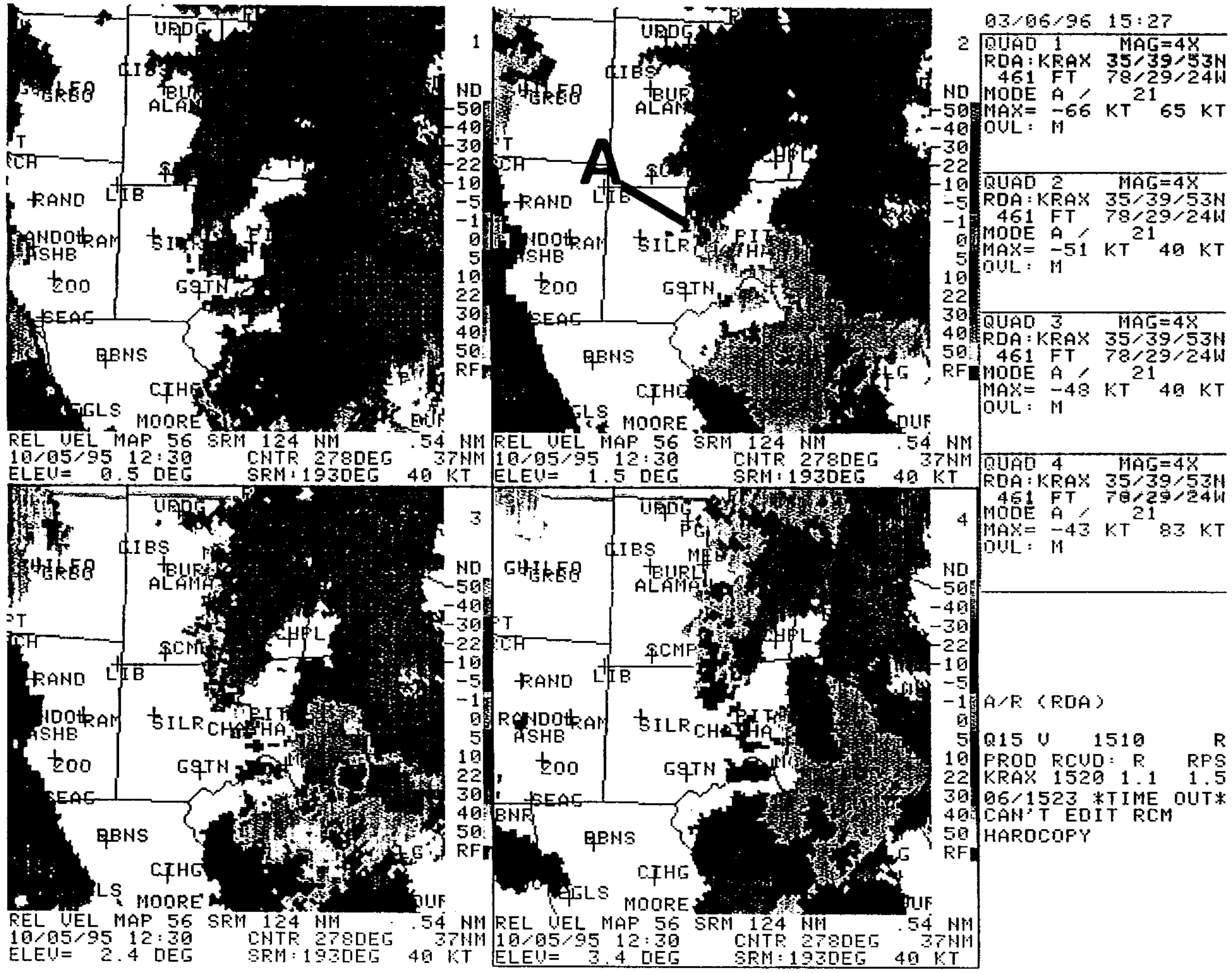


Figure 2.5. WSR-88D four-panel velocity for Chatham County at 1230 UTC (08:30 EST) on 05 Oct. 1995.

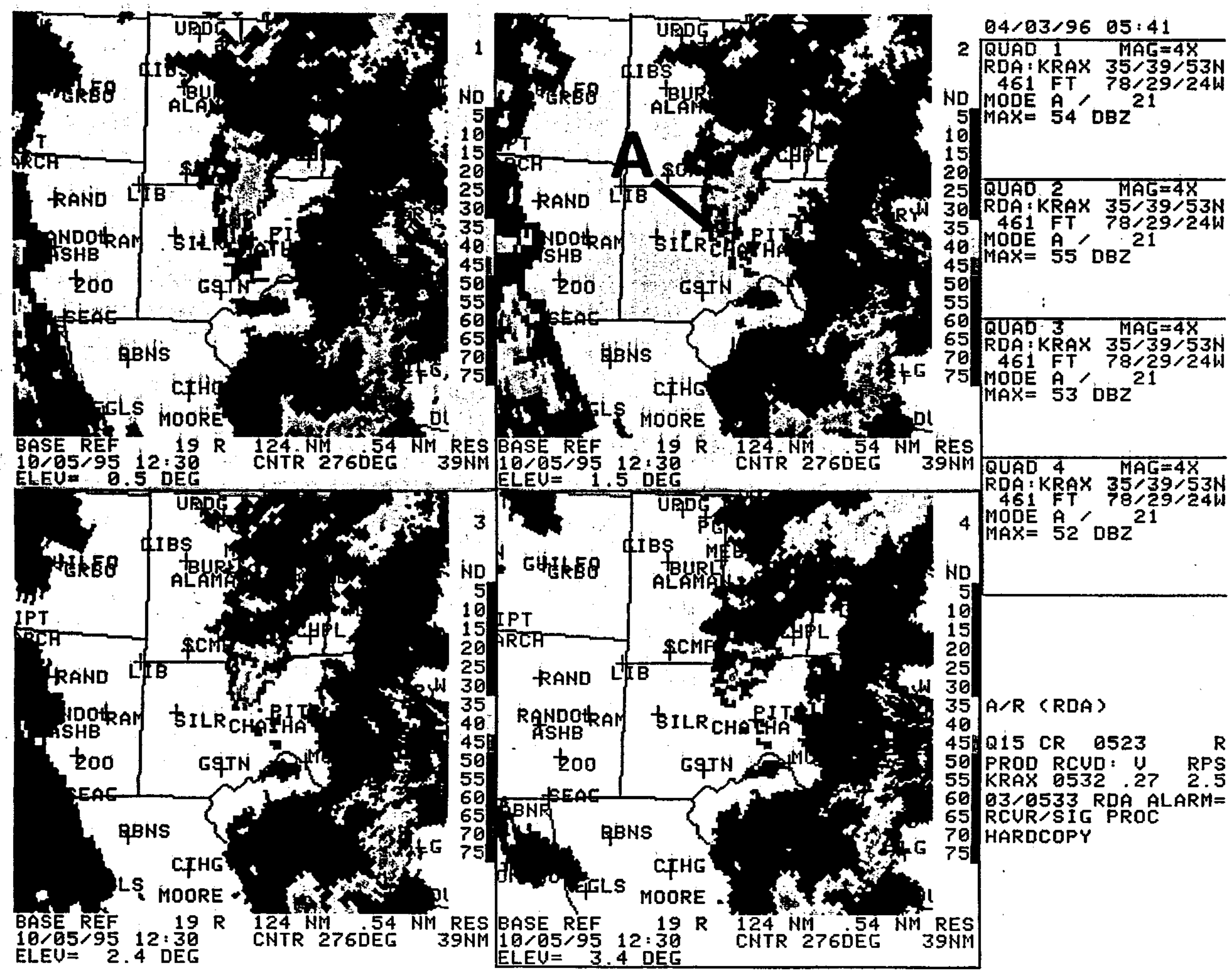


Figure 2.6. WSR-88D four-panel reflectivity for Chatham County at 1230 UTC (08:30 EST) on 05 Oct. 1995.

of 50 to 55 dBZ in cell A. Based on the increased shear values, the decision is made to issue a warning.

08:37 The tornado warning is issued for Chatham County.

08:40 The radar operator is looking at the base reflectivity. There is a weak pendant on the south side of the cell in north-central Chatham County. A call is initiated to Chatham County. They report trees down. [Initiator]

08:42 A report is received of a possible tornado near Pittsboro in Chatham County.

08:45 The Blacksburg, VA NWS Office calls regarding the conditions in the RWA.

08:47 The relative velocity magnified four times shows 19 knots of shear in the Chatham County cell which is now entering Orange County.

08:48 The radar operator is continuing to monitor the relative velocity at four-times-magnification. The gate-to-gate shear is now up to 25 knots in the above cell. [Trigger]

08:50 The radar operator recommends that a warning be issued for Orange County based on the shear values and the reports verifying the Chatham County warning.

08:51 The Orange County tornado warning is issued.

08:52 The cell has a reflectivity structure suggestive of a supercell.

08:53 The cell is now positioned in southwest Orange County and still shows good organization on the four panel reflectivity.

08:54 The relative velocity shows 19 knots of shear. A call is initiated to Orange County.

08:55 There is now 21 knots of gate-to-gate shear in the above cell.

08:58 It is noted that cells are moving very rapidly. Chatham County is now clear and the warning is being pulled off of the weather radio tape. The relative velocity for 1254 UTC scan reveals 19 knots of shear.

09:11 The radar operator is looking at the relative velocity for the entire warning area and notes that the only organized shear is in Orange County.

09:15 The shear in Orange County extends to 10,000 feet.

09:20 The relative velocity on the 13:17 UTC scan shows that the cell in Orange County seems to becoming less organized.

The second case is taken from June 16, 1995 and illustrates a much more active severe weather episode with four warnings issued for three different cells in less than thirty minutes. For the previous five days, severe weather had developed in unstable air ahead of an approaching cold front. So far, however, the convection has produced only marginal severe weather with mostly scattered wind damage and some dime-size hail. The surface analysis given in Fig. 2.7 shows the position of a surface cold front at 2000 UTC (16:00 EDT) for this case. Ahead of the front there has been some clearing and destabilization. Also notice the abundant moisture with dew points in the 70's over much of the eastern Carolinas--in the eastern part of the RWA.

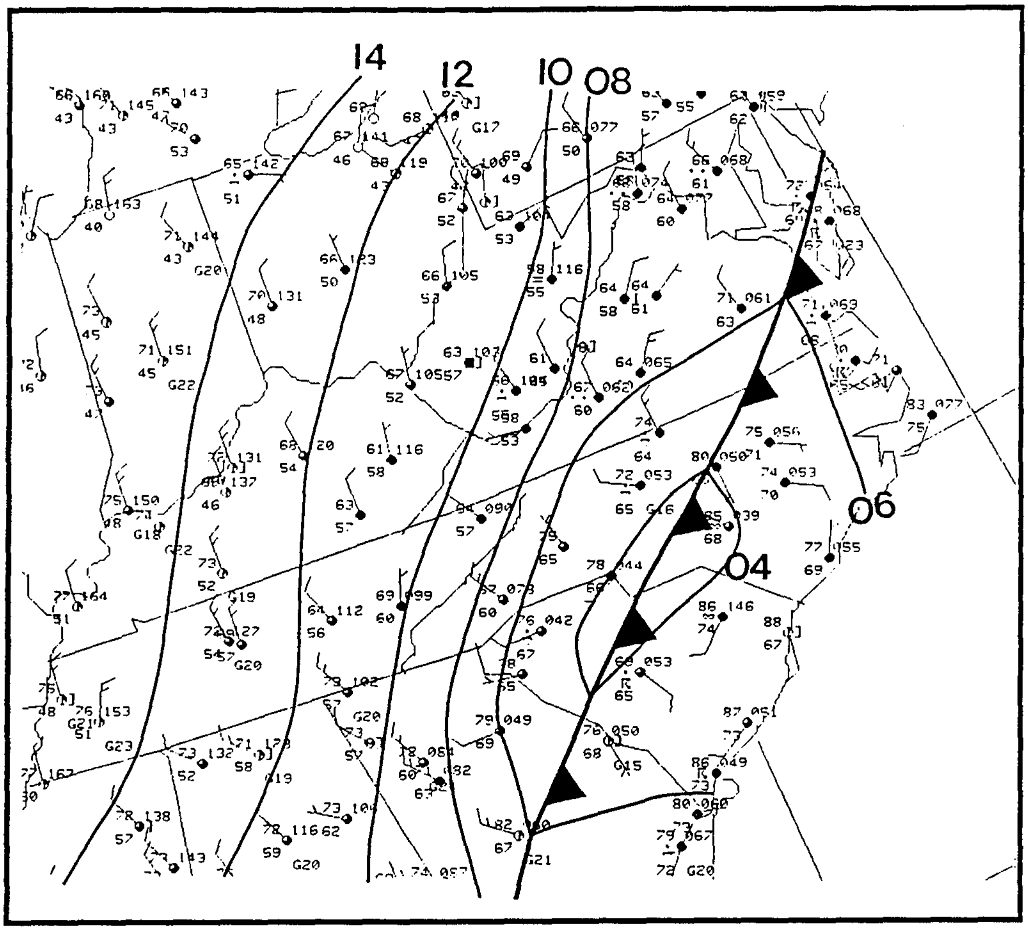


Figure 2.7. Surface analysis for 2000 UTC 12 Jun. 1995

Figure 2.8 shows the 1200 UTC sounding for Moorehead City, NC. This sounding was selected because it was ahead of the rain cooled air and was the last sounding available to the operational forecaster. Even without surface modification, the CAPE is 2478 m^2/s^2 which is supportive of strong convection. However, the storm

relative helicity is only 24 m^2/s^2, a value not supportive of supercells. Thus, pulse-type convection with possible hail and straight line wind damage are anticipated.

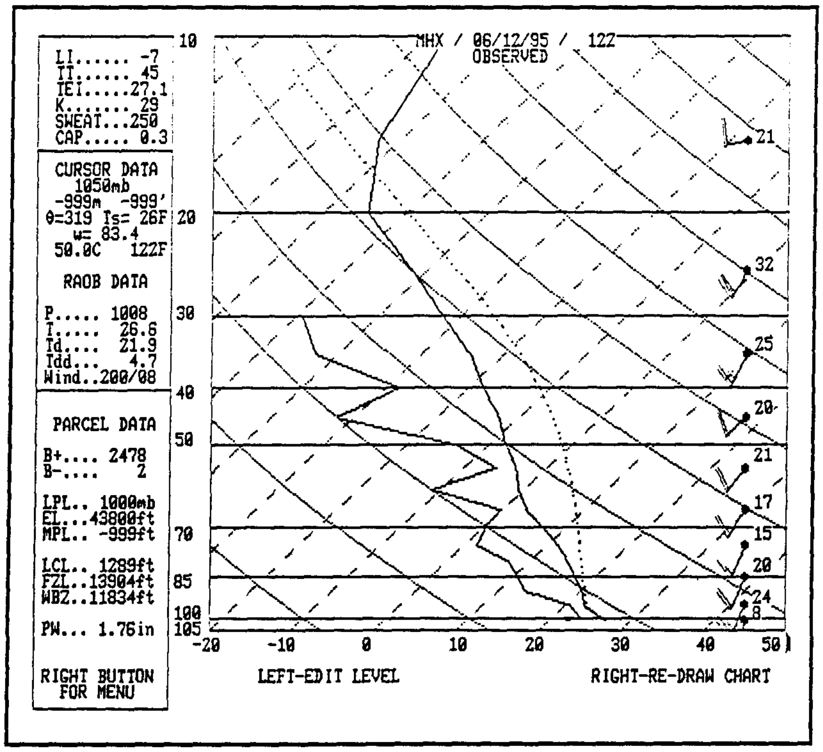


Figure 2.8. 1200 UTC 12 Jun. 1995 skew T-log *p* plot of Moorehead City, NC (MHX).

Now the SWATR for the first four warnings will be presented with times given in EDT. Figure 2.9 is the location map for this example. In order to keep track of all the severe and potentially severe cells, several convective lines and cells are labeled in Fig. 2.11. The labeling convention will be used throughout this excerpt from the SWATR. However, the reader is cautioned to keep in mind that the lines and cells are evolving during the episode and the changing locations of the cells will be noted in the excerpt. Finally, Fig. 2.10 is a flow chart of the warnings issued during the excerpt.

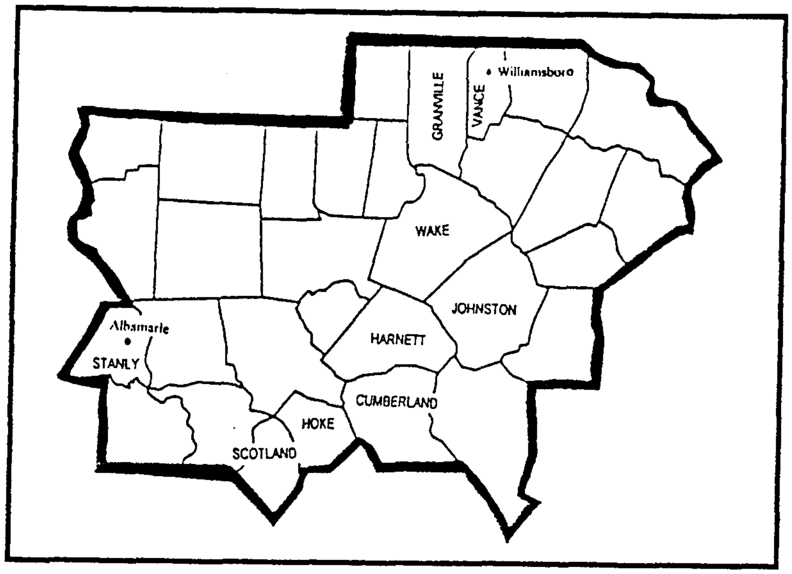


Figure 2.9. Location map for 12 Jun. 1995 case.

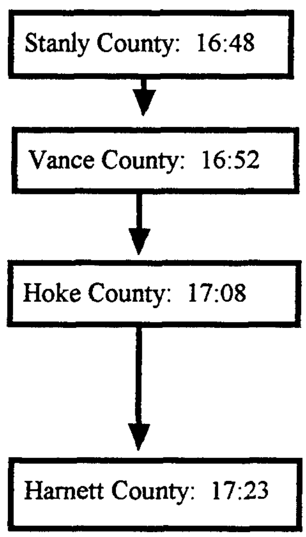


Figure 2.10. Flow chart of the warnings issued during the 12 Jun. 1995 case. All warnings are severe thunderstorm warnings. The times given are in EDT.

16:44 The RDU WFO received word that the Charlotte WFO had issued a severe thunderstorm warning for cell A in Union County immediately southwest of Stanly County.

16:45 Cell A is located six or seven miles south of Albamarle in Stanly County and has a reflectivity of 65 dBZ. [Trigger] The decision is made to issue a severe thunderstorm warning for Stanly County. Note that Figure 2.10 is the composite reflectivity for the 2047 UTC (16:47 EDT) scan showing that cell A is a small intense cell entering western Stanly County.

16:48 The warning for cell A is issued for Stanly County. The radar operator is looking at the storm relative velocity in line C over Hoke County.

16:49 Cell B in northwest Vance County has reflectivity values from 55 to 60 dBZ. The radar operator obtains a cross section of the cell showing a maximum core of 65 dBZ with good southward overhang. [Trigger] The decision is made to issue a warning for northern Vance County.

16:50 A mesocyclone alert sounds for a strong cell in Cumberland County in the northeastern section of line C.

16:52 The severe thunderstorm warning on cell B for Vance County is transmitted.

16:53 The radar operator is looking at the four-panel velocity in Cumberland County in the northeastern region of line C.

16:54 Ground truth reports are solicited from Cumberland and Harnett Counties in the northeastern regions of line C. There have been no hail or damage reports. A severe thunderstorm warning is prepared for Granville County as the central

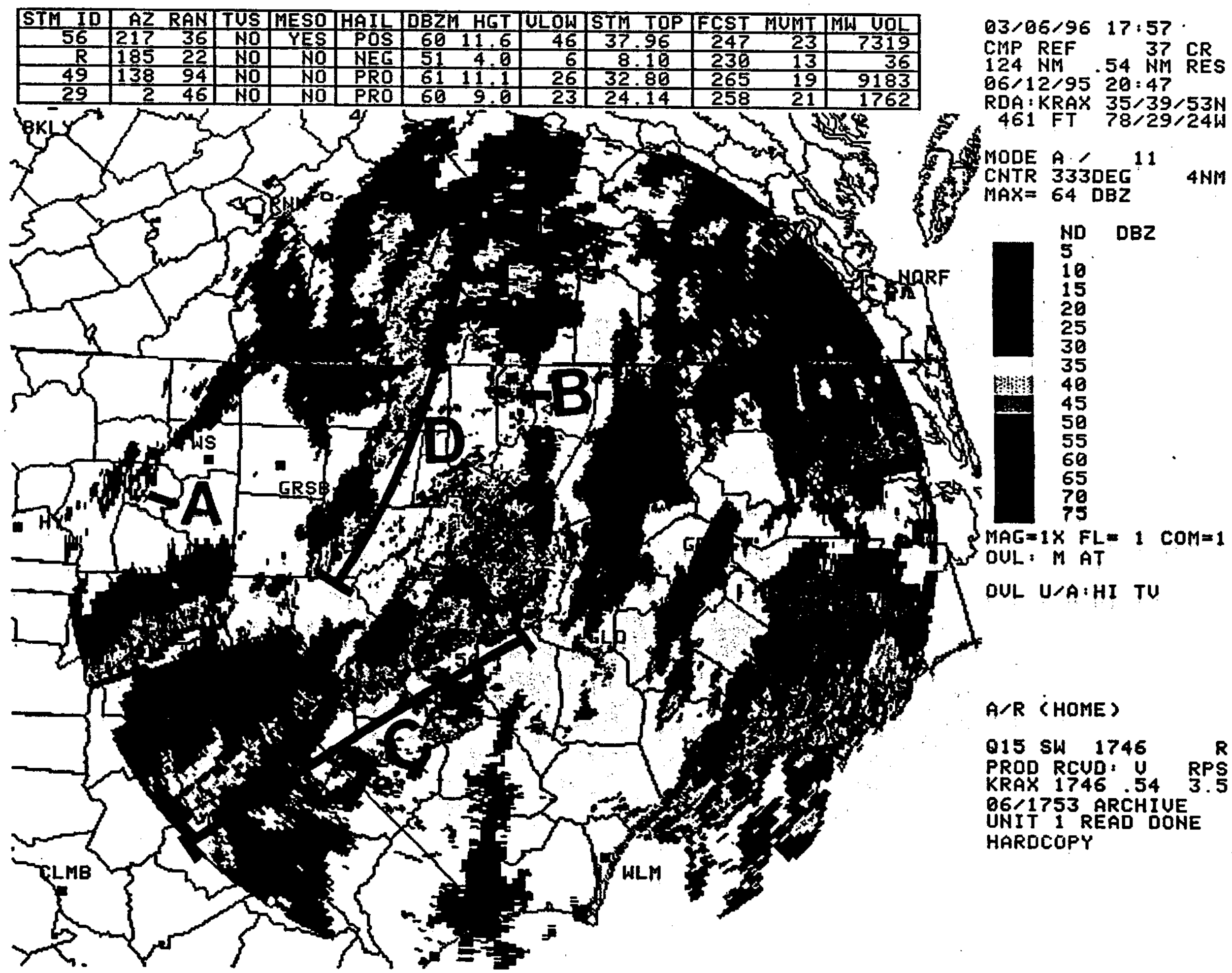


Figure 2.11. WSR-88D composite reflectivity for 2047 UTC (16:47 EDT) on 12 Jun. 1995.

section of line D approaches from the west. The warning will be held until a decision is made whether or not it should be issued.

16:55 A storm cell is noted over east-central Wake County.

16:56 Granville County reports no severe weather associated with line D.

16:57 The VIL has decreased on the Granville County cell. Because of this decrease in the VIL and the above ground truth report, the decision is made not to warn Granville County for line D.

16:58 A special weather statement is started for Wake, Johnston and Harnett Counties.

17:01 Looking at the northeastern regions of line C, the four panel reflectivity for Hoke County is not impressive.

17:02 A hail alert is present for Granville County on line D. Granville County is called for reports.

17:05 The reflectivity values are now 65 dBZ in a cell in western Hoke County in the northeastern region of line C [Trigger]. The decision is made to warn Hoke County.

17:06 A mesocyclone alert sounds for northern Cumberland County in the northeastern region of line C.

17:07 The VIL is now 45 to 50 kg/m^2 in Hoke County and northern Cumberland County in the northeastern region of line C.

17:08 The Hoke County warning is transmitted for a segment of line C.

17:09 Vance County is called for damage reports associated with cell B. There is 3-D correlated shear indicated east of Williamsboro in Vance County.

17:11 Stanly County is called for damage reports form cell A.

17:12 The radar operator is looking at a cross-section of the cell in northern Cumberland County on line C. It does not look impressive.

17:13 The composite reflectivity shows 60 dBZ or more on line C in northern Cumberland County. [Initiator]

17:14 The radar operator is analyzing the four panel reflectivity for northern Cumberland County. There is a report of 3/4 inch hail from Hoke County which is also on line C.

17:16 The VIL is 50 kg/m^2 in southwest Hoke County on the county line.

17:19 The radar operator is considering warning Harnett County for cell E shown on Fig. 2.11. A call is initiated to Harnett County for possible reports. A cross section of cell E in Harnett County is given in Fig. 2.12 and shows 50 dBZ extending to about 20,000 feet. The core is around 55 dBZ and shows some overhang. [Trigger]

17:20 The decision is made to issue a severe thunderstorm warning for Harnett County.

17:21 There is a report of marble size hail in Scotland County associated with line C.

17:22 A warning is prepared for Scotland County and is held until the decision is made whether or not a warning should be issued.

17:23 The Harnett County warning is transmitted.

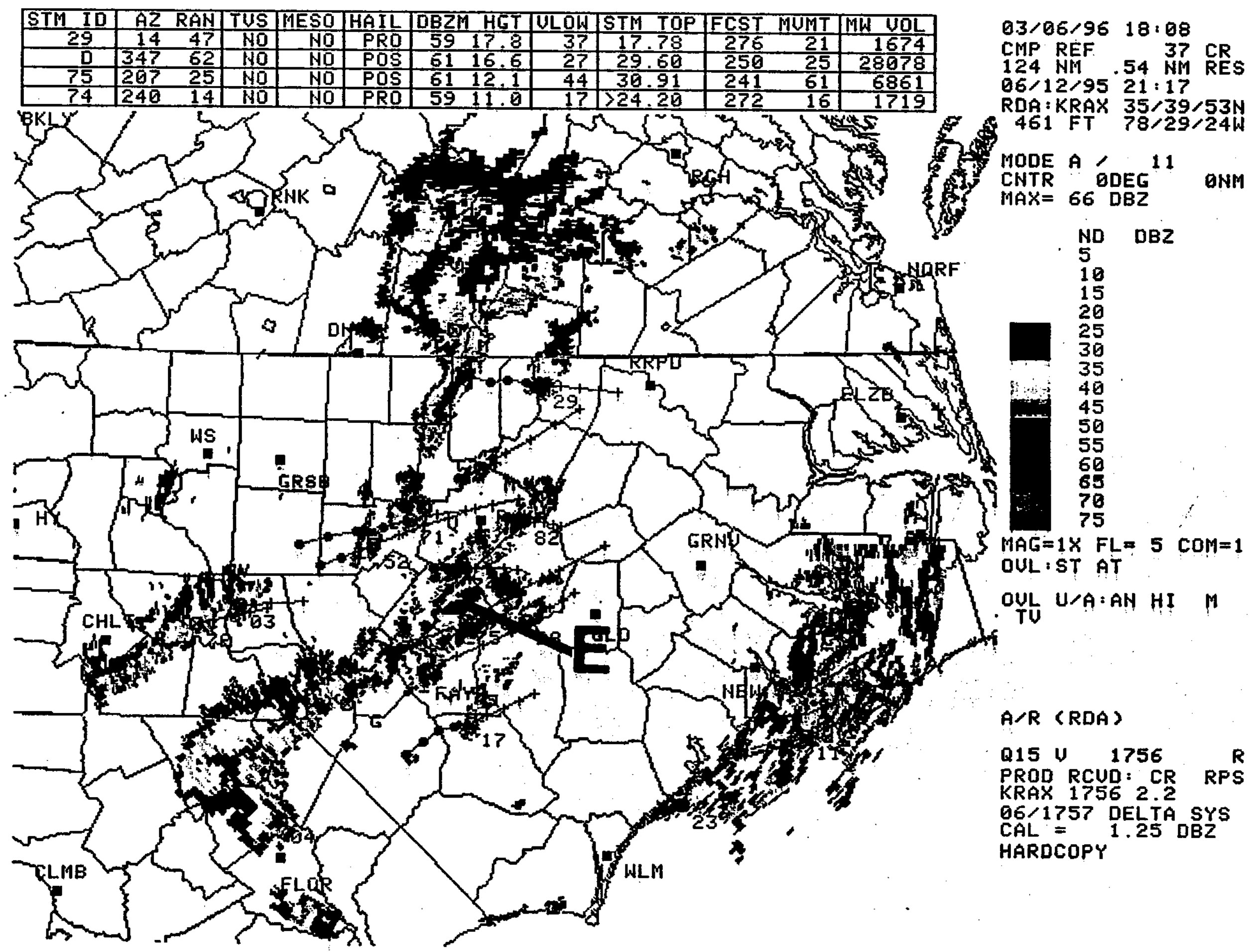


Figure 2.12. WSR-88D composite reflectivity for 2117 UTC (17:17 EDT) on 12 Jun. 1995.

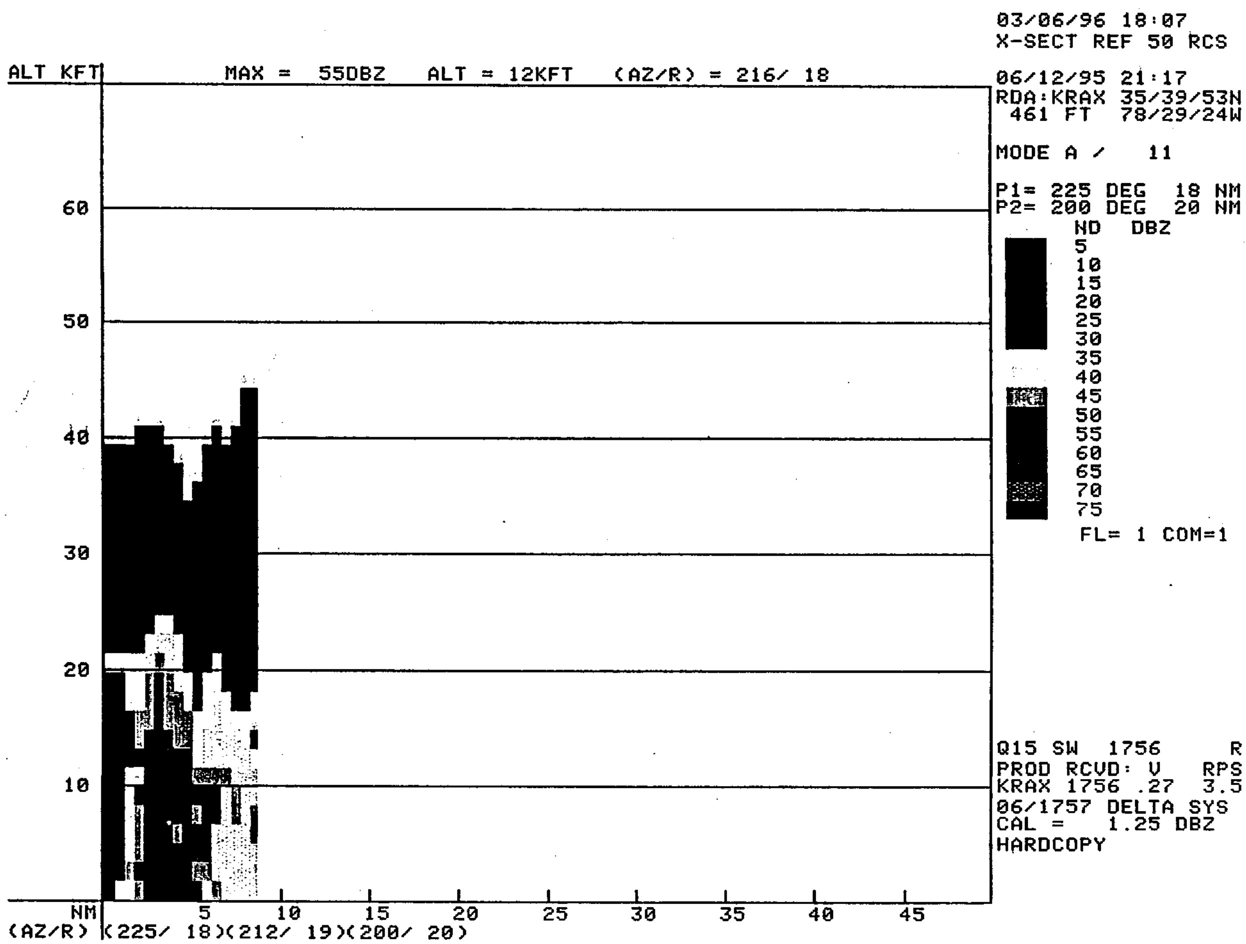


Figure 2.13. A southwest to northeast WSR-88D cross section of cell E indicated in Fig. 2.12.

The warning was never issued for Scotland County because conditions did not intensify. However, an additional seven warnings were issued during this severe weather episode.

These two case studies have been included to illustrate the activity at the WSR-88D PUP during a severe weather episode. The first case was a slow paced event where the radar operator's attention was entirely focused on an individual intense cell. In contrast, the second case was included to illustrate the opposite extreme where the radar operator must quickly investigate multiple severe cells. The activity level for most severe weather episodes fall somewhere between the two cases provided in this chapter. The remainder of this report will be a more general examination of the warning process using these cases to illustrate the points made.

3. SCHEMATIC REPRESENTATION OF THE WARNING PROCESS

As illustrated by the case studies in the previous chapter, the warning process includes a complex series of events leading a forecaster to a decision to (or not to) issue a warning. Keep in mind throughout this chapter that the forecaster is often dealing with multiple warnings at different phases in the warning process as shown by the second case. However, to gain an understanding of how the process operates, the labyrinth has been simplified to include the sequence of key events common to in the issuing of all warnings.

The schematic representation of the warning process presented in Fig. 3.1 was developed from the PDS and illustrates how the forecaster progresses from monitoring the situation to issuing a warning. Usually some event, defined here as the initiator, prompts the radar operator to perform further investigation on a given cell and to consider issuing a warning. In some cases, the decision is made not to issue a warning. Otherwise, a second key event, called the trigger, leads to drives the decision to issue the warning. In some circumstances, the warning has only a trigger followed by the immediate issuing of the warning as shown by both of the dashed paths in Fig. 3.1. This class of warning will be called the immediate trigger warnings. After the warning has been issued, ground truth reports are commonly sought which can lead to the verification of the warning.

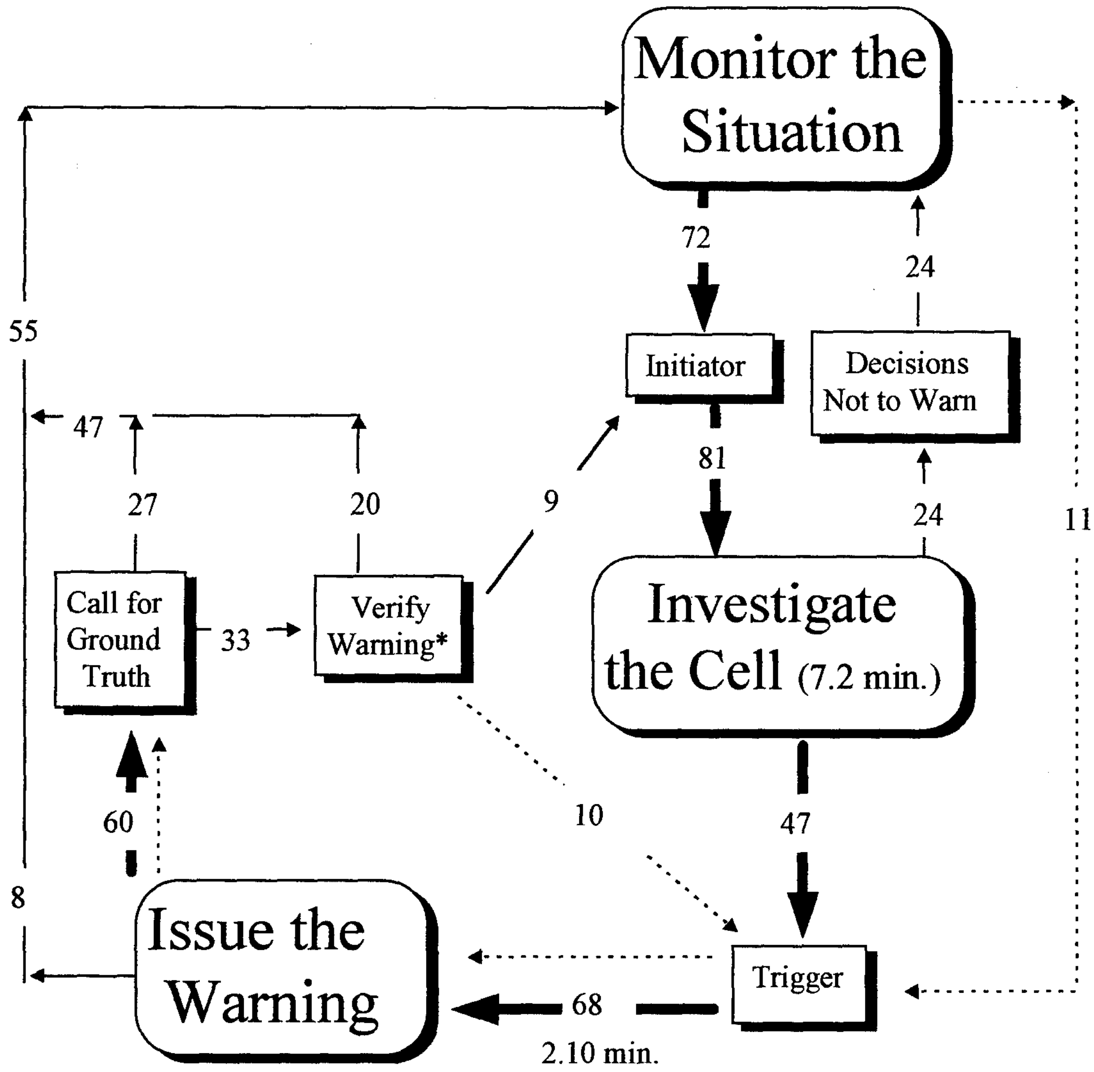


Figure 3.1. This schematic representation of the warning process traces the sequence of events leading a forecaster to a warn or no-warn decision for an individual cell. The numbers represent the number of times a forecaster was along each path. The asterisk in the verify warning box represents the six warnings whose initiator was a previous verification for a preceding warning that was not documented. The bold track is taken most often. The two dotted cycles are immediate trigger warnings.

The utilized radar products and ground truth reports provide information that serves as the initiator, trigger and decisions not to warn. Table 3.1 lists the broad and subcategories of this information. Note that the first three subcategories are a breakdown

of the reflectivity, 'R', category, the next two subcategories are derived from the velocity, 'Ve', category, and finally the last three subcategories are the components of the ground truth, 'G', category. In analyzing the initiator and trigger, the text will refer to these categories of activities as the initiators and the triggers. Clearly, specific information is lost by categorizing activities and therefore Appendix 7.3 contains the detailed listing of initiators, triggers, and decisions not to warn.

Table 3.1. The broad categories and subcategories used in the analysis of the initiator, trigger and decisions not to warn.

	BROAD CATEGORIES
R	Reflectivity based Doppler radar products
Ve	Velocity based Doppler radar products
G	Ground truth reports
	SUBCATEGORIES
R	Base or composite reflectivity
Vi	Vertically Integrated Liquid (VIL)
X	Reflectivity cross section
M	Mesocyclone
Ve	Any base or Storm Relative Velocity Product
T	In the track of a previously verified cell
C+	Immediate call with a report of a severe thunderstorm or tornado in or very near the county warned
C-	Immediate call with a report of weather that does not meet severe thunderstorm or tornado criteria in or very near the warned county

Notice from Table 3.1 that one of the categories of activity is ground truth reports. To avoid confusion, it is important to note that the "Call for Ground Truth" box in Figure 3.1 is located in the most common position for reports to be sought, but it is not the only time calls occur. Throughout the warning process, the NWS personnel are initiating and

receiving ground truth reports from the public as shown in the cases presented in chapter two. These ground truth reports often become the initiator, trigger or rationale for a decision not to warn.

The remainder of this chapter steps through each block of Fig. 3.1 giving both a qualitative and quantitative analysis of the warning process. In numeric computations, the data set is often a subset of the PDS because of incomplete documentation. However, in order for the totals entering the blocks to balance with those exiting, the numbers in Fig. 3.1 include the entire PDS.

3.1 Monitor the Situation

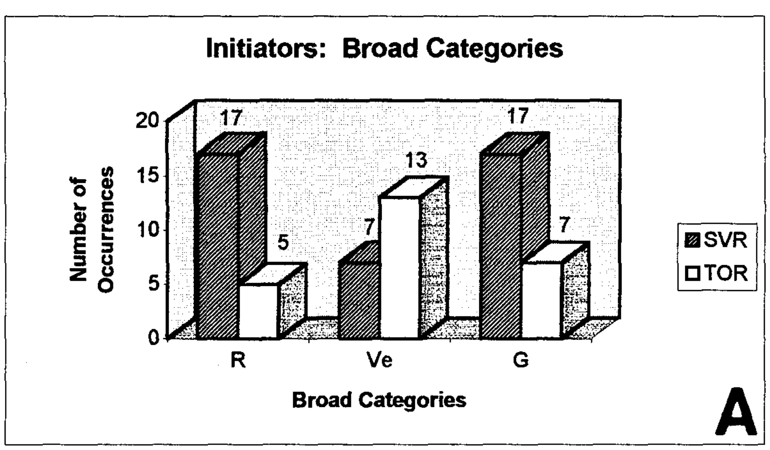
When there is a threat of severe weather, the radar operator monitors the situation throughout the county warning area. This phase can last for hours or quickly become focused with the development of an initiator or a trigger.

3.2 The Initiator

The initiator is the event that prompts the radar operator to investigate a potentially severe cell and consider issuing a warning. To ensure statistical independence, each initiator is linked to only one of the categories listed in Table 3.1. It is important to note that the initiator is only separated from the trigger in cases where there was at least two minutes of investigation prior to the decision to issue the warning. Often the SWATR clearly states the radar operator is considering issuing a warning, and hence the initiator can easily be determined.

However, for other warnings it is more difficult to determine the exact initiator, and therefore it must be determined indirectly by proceeding backwards from an issued warning or documented decision not to warn. In these cases, the initiator is the first activity documented where the radar operator is investigating an individual cell and is considering issuing a warning. An example of an initiator found indirectly is the initiator for the Harnett County warning in case two at 17:13 EDT. There is ambiguity in the determination of this initiator. The radar operator is focusing on the Harnett County cell when a cross section was performed at 17:12 EDT . However, since the cross-section is not impressive, it does not prompt the radar operator to consider issuing a warning and hence is not the initiator.

Finally, there are 15 cases where the documentation indicates the radar operator is investigating a cell and considering issuing a warning but the SWATR does not specify the initiator. Therefore, out of the 81 cases in Fig. 3.1, a total of 66 warnings, 41 severe thunderstorm and 25 tornado warnings are included in the following analysis. Figure 3.2 shows the distribution of initiators for issuing severe thunderstorm and tornado warnings.



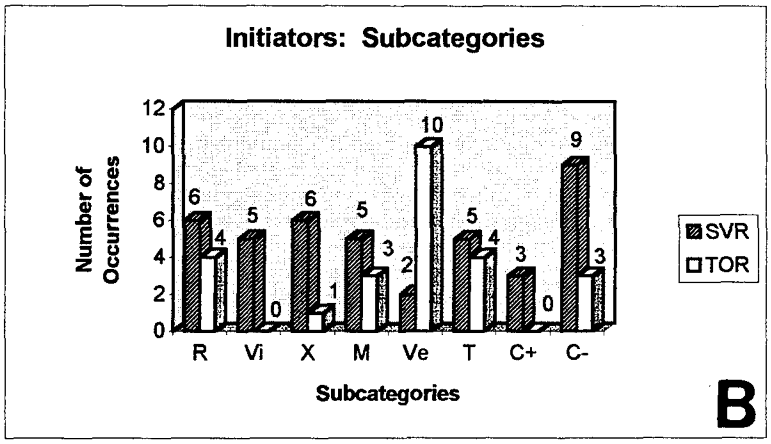


Figure 3.2. Initiators for severe thunderstorm (SVR) and tornado (TOR) warnings. Figure 3.2A used the broad categories while Fig. 3.2B utilizes the subcategories. Table 3.1 defines the categories. A total of 41 severe thunderstorm warnings and 25 tornado warnings are included. The numbers above the columns are the column totals which will be used in the statistical analysis that follows.

A contingency table was used to analyze the statistical contrasts between the initiators for both severe thunderstorm and tornado warnings. The following example illustrates this test for severe thunderstorm warnings using the broad categories of activities. The null hypothesis, H_o, for a statistical test is the statement to be disproved. In this case, H_o states that the probability of severe thunderstorms having each of the three initiators is the same. Before the test can be presented, the following variables must be defined (Mendenhall and Sincich, 1992):

P_i = the hypothesized probability of being in category i. Under the null hypothesis, P_i must be $\left(\frac{1}{3}\right)$ for each initiator.

obs = the observed number of warnings with each initiator. The figure above shows that reflectivity is the initiator for 17 warnings, velocity for 7 warnings, and ground truth for 17 warnings.

n = the sample size. In this case, n=41.

exp $= n\,(P_i) = 41 \left(\frac{1}{3}\right) = 13\frac{2}{3}$, the expected count for each initiator.

Now, the following assumptions must be met for this test to be used (Mendenhall and Sincich, 1992):

1) The trials must be identical. In this case, each warning used in the initiator analysis is a trial. The initiators for severe thunderstorm and tornado warnings have been separated in this analysis in an attempt to make the trials identical. The PDS is too small to make further divisions.

2) There are k possible outcomes for each trial. For this example there are three initiators and hence k=3.

3) The hypothesized probabilities must sum to one, $\sum_i P_i = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$

4) The trials must be independent. This is why only one category of activity is the initiator for each warning.

5) The random variables must be counts for each cell.

6) The sampling size, n, must be "large". The test of this assumption is as follows,

exp ≥ 5, for all k categories. For this example, exp $= 13\frac{2}{3}$ for all initiators and thus this final assumption is met.

Now that the variables have been defined and the assumptions met, the statistical test can be presented. Table 3.2 is the contingency table for this example.

Table 3.2. The contingency table for this example--severe thunderstorm warnings with the three broad categories of initiators. The variables are defined in the text above.

OCCURRENCES

		Obs	Exp=n(Pi)
INITIATORS	R	17	13.67
	Ve	7	13.67
	G	17	13.67
	Total	41	

The test statistic, X^2, has approximately a Chi Square distribution for large sample sizes and is defined as follows:

$$X^2 = \sum_k \frac{(obs - \exp)^2}{\exp} = \frac{(17 - 13.67)^2}{13.67.} + \frac{(7 - 13.67)^2}{13.67} + \frac{(17 - 13.67)^2}{13.67} = 4.88$$

with (k-1) = 2 degrees of freedom.

To reject H_o, X^2 must be greater than χ^2_{crit} where χ^2_{crit} is the critical value of the Chi Square distribution for the given confidence level and degrees of freedom. In this statistical test and for the remainder of this report, the confidence level will be 0.05. For this case, $\chi^2_{crit} = 5.99$ and hence H_o cannot be rejected. Therefore, the conclusion is that there is not statistically significant evidence of any differences in the initiator probabilities for severe thunderstorm warnings.

This same analysis can be used with the subcategories and for tornado warnings as summarized in Table 3.3.

Table 3.3. The statistical results for initiators. The test determines the differences between the broad and subcategories of initiators for SVR and TOR warnings.

Statistical Results: The Initiator						
	n	**P_i**	**exp**	**X^2**	χ^2_{crit}	**Conclusion**
SVR						
broad categories	41	0.333	13.67	4.88	5.99	Fail to Reject H_o
subcategories	41	0.125	5.125	6.03	14.1	Fail to Reject H_o
TOR						
broad categories	20	0.333	8.33	4.16	5.99	Fail to Reject H_o
subcategories	20	0.125	3.125	Insufficient Sample Size		

The first test summarizes the example given above. The next two tests have the same conclusion as the example, a failure to reject H_o. Notice that the last test was not completed because of a failure to meet the assumption of a "large" sample size. So it is found that no statistically significant conclusions can be made concerning the initiators. Therefore, none of the initiators appear to be used more than others.

3.3 Investigate the Cell

By definition, the only exit from the initiator block is to investigate the cell. The investigation time is defined as the time between the initiator and the trigger. The average investigation time is 7.2 minutes. However, this average is skewed high because of a few long periods of investigation. The median of the distribution is five minutes and the mode is only three minutes. Figure 3.3 illustrates the distribution of investigation times.

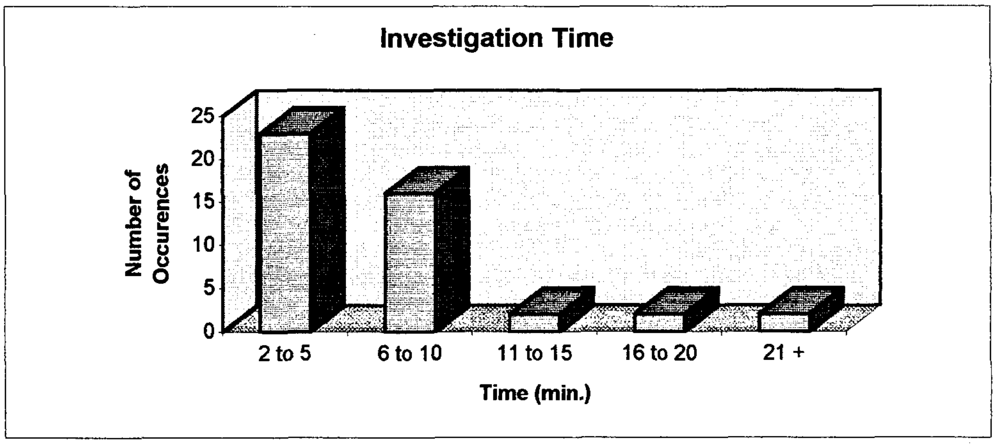


Figure 3.3. The distribution of investigation times.

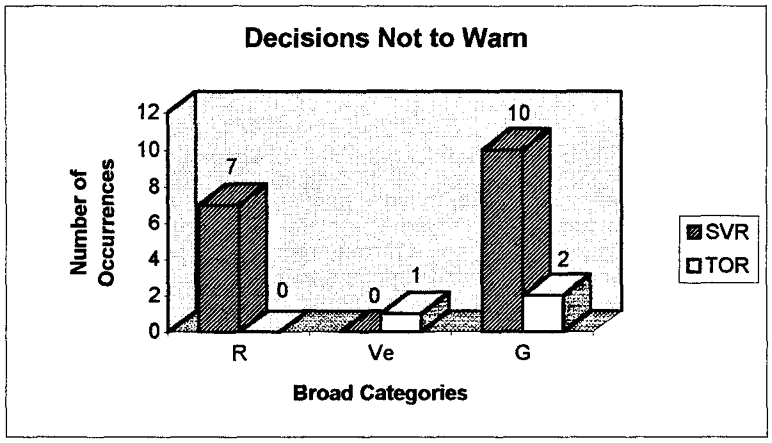
Long investigation times are not necessarily undesirable but simply indicate that the radar operator was focused on an individual cell for a long period of time. During episodes with many warnings, the radar operator has less time to focus on individual cells and therefore the investigation times are generally shorter.

Out of the "Investigate the Cell" phase, the radar operator either encounters a trigger and recommends that a warning be issued or the decision is made not to issue the warning. The latter of these options will be discussed first.

3.4 Decisions Not to Warn

There are 24 documented decisions not to warn. However, only 20 of these decisions had a clearly defined category of activity. Figure 3.4 illustrates the distribution of categories of activities for decisions not to warn. Only the broad categories are included because the documentation is not detailed enough to break the decisions into

subcategories and there are not enough warnings to differentiate statistically one subcategory from another.



Figures 3.4. The broad categories of activity leading to a decision not to issue a warning. Table 3.1 defines the categories of activities. Decisions not to issue a total of 17 severe thunderstorm warnings and 3 tornado warnings are included. The numbers above the columns are the column totals which will be used in the statistical analysis that follows.

Notice also that when all warnings are considered, 12 of the 20 decisions not to issue warnings are triggered by ground truth reports. These decisions are usually made when the storm coordinator knows that the cell is directly over a populated area, and yet initiated and received ground truth reports do not indicate severe weather is occurring.

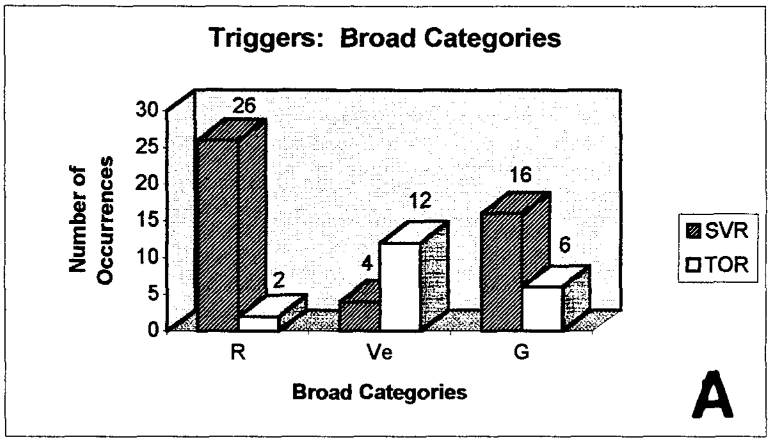
From the statistics provided in Table 3.4, notice that H_o is rejected for severe thunderstorm warnings. The strict conclusion is that P_i is not equal to 1/3 for at least one of the categories of activities. However, from the data illustrated in Fig. 3.4, it can be inferred that decisions not to issue severe thunderstorm warnings are more likely to be triggered by ground truth reports or reflectivity based products than velocity based products.

Table 3.4. The contingency table results for the decisions not to warn. The test determines the differences between the broad categories of activity for decisions not to issue SVR and TOR warnings.

Statistical Results: Decisions Not to Warn						
	n	P_i	exp	X^2	χ^2_{crit}	Conclusion
SVR						
broad categories	17	0.333	5.67	9.29	5.99	Reject H_o
TOR						
broad categories	3	0.333	1	Insufficient Sample Size		

3.5 The Trigger

Except for the decisions not to warn, the only other passage out of the "Investigate the Cell" block is to encounter a trigger. Notice also from Figure 3.1 that the radar operator can also reach the trigger block directly from monitoring the situation or from the verification of a previous warning. The trigger is defined as that which causes the radar operator to make the decision to issue a warning. Recall that sample independence is a fundamental assumption for using a contingency table and therefore each trigger is categorized by only one category of activity from Table 3.1. In the SWATR, the rationale for some warnings is clearly stated and thus the trigger is easily pinpointed. If more than one category of activity is listed as the rationale for issuing the warning, the last documented activity is used as the trigger. Similarly, in cases where the reasoning for the issuance of a warning is not explicitly stated, the trigger is taken to be the last documented activity prior to the issuing of the warning. The following figures show the distribution of triggers.



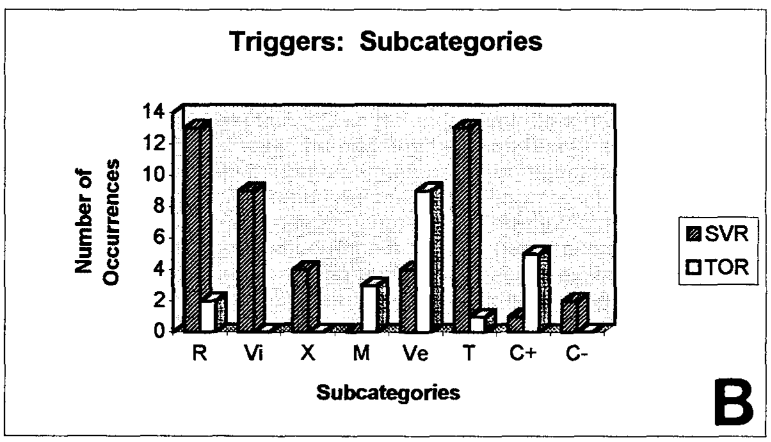


Figure 3.5. The triggers for issuing severe thunderstorm (SVR) and tornado (TOR) warnings. Figure 3.5A uses the broad categories while Fig. 3.5B utilizes the subcategories of triggers. Table 3.1 defines the categories of activities. A total of 46 severe thunderstorm warnings and 20 tornado warnings are included. The numbers above the columns are the column totals which will be used in the statistical analysis that follows.

Three statistically significant conclusions can be about the warning triggers as shown in Table 3.5.

Table 3.5. The statistical results for the trigger. The test determines the differences between the broad and subcategories of triggers for SVR and TOR warnings.

Statistical Results: The Trigger						
	n	P_i	exp	X^2	X^2_{crit}	Conclusion
SVR						
broad categories	46	0.333	15.333	15.826	5.99	Reject H_o
subcategories	46	0.125	5.75	33.304	14.1	Reject H_o
TOR						
broad categories	20	0.333	6.667	7.6	5.99	Reject H_o
subcategories	20	0.125	2.5	Insufficient Sample Size		

From the rejection of H_o for the broad categories of severe thunderstorm triggers, it can be inferred that for a greater number of severe thunderstorm warnings are triggered by reflectivity based radar products than velocity products. The null hypothesis is also rejected for the subcategories of triggers for severe thunderstorm warnings. However, in this case there is no clear inference and therefore the only conclusion that can be made is that P_i is not equal to 1/8 for at least one of the subcategories. Finally, with the broad categories of triggers for tornado warnings, it can be concluded that the trigger is more likely to be velocity based than reflectivity based.

3.6 Immediate Trigger Warnings

A subset of the warnings entering the "trigger" block do not come from the investigation of a cell. These warnings are the immediate trigger warnings and eleven come directly from the "monitor the situation" block while ten are from the "verify warning" box. These 21 documented immediate trigger warnings are all severe thunderstorm warnings. Therefore, for the PDS, there was an initiator and an investigation of the cell prior to all 20 tornado warnings. This indicates that the radar operator is more hesitant to recommend that a tornado warning should be issued and

he/she takes time to investigate the cell. Figure 3.6 shows the breakdown of trigger categories for the immediate trigger warnings.

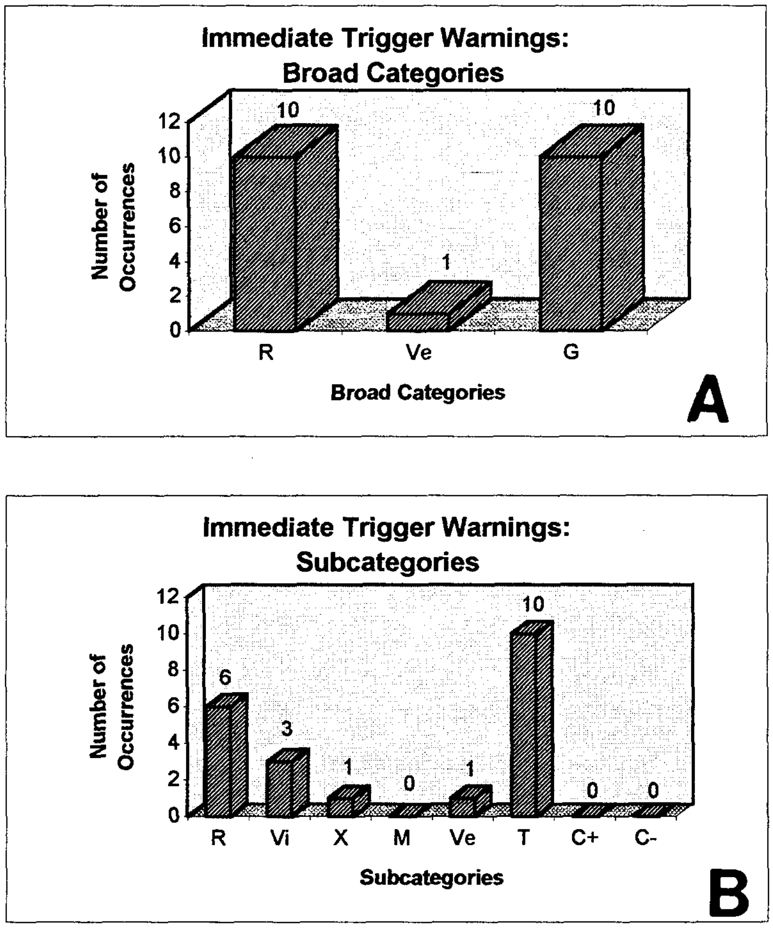


Figure 3.6. The triggers for immediate trigger warnings. Figure 3.6A uses the broad categories while 3.6B utilizes the subcategories of triggers. Table 3.1 defines the categories. All 21 immediate trigger warnings are severe thunderstorm warnings. The numbers are the column totals, which will be used in the statistical analysis that follows.

Immediate trigger warnings are a subset of all triggers which were presented in section 3.5. Notice that 48 percent of the immediate trigger warnings are triggered by ground truth reports. However, from Fig. 3.5 only 33 percent of the triggers for all severe thunderstorm warnings are ground truth reports. Now comparing Figs. 3.5 to Fig. 3.6,

there are 16 total severe thunderstorm warnings triggered by ground truth reports, and 10 of these 16 were immediate trigger warnings. This indicates that while ground truth reports are not the most common trigger for severe thunderstorm warnings, they often cause warnings to be immediately issued. Table 3.6 presents the statistical results.

Table 3.6. The statistical results for immediate trigger warnings. The test determines the differences between the broad and subcategories of triggers for SVR warnings. There are no immediate trigger tornado warnings in the PDS.

Statistical Results: Immediate Trigger Warnings						
	n	**P_i**	**exp**	**X^2**	**χ^2_{crit}**	**Conclusion**
SVR						
broad categories	21	0.333	7	7.71	5.99	Reject H_o
subcategories	21	0.125	2.625	Insufficient Sample Size		

From the rejection of H_o for the broad categories of triggers, it can be concluded that ground truth reports and reflectivity based products are the most common immediate triggers for more severe thunderstorm warnings. Notice that the sample size was too small to analyze the subcategories of activities.

3.7 Issue the Warning

The only exit from the "trigger" block is to issue the warning. An analysis of the warning preparation time will now be presented. The preparation time is defined as the time elapsed from the decision to issue the warning, the trigger, to the issuance of the warning. Figure 3.7 shows the distribution of preparation times for warnings.

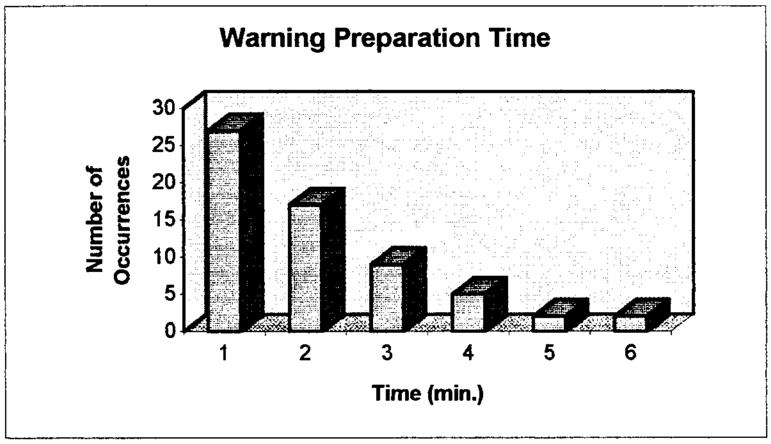


Figure 3.7. The warning preparation time for the PDS for severe thunderstorm and tornado warnings.

The average preparation time for a warning was 2.1 minutes with a median of two minutes and a mode of one minute. Notice that all documented warnings were transmitted within six minutes of the decision to issue the warning.

The warnings with the shortest preparation times were likely prepared during the investigation of the cell and were ready to be transmitted as soon as a trigger occurred. However, there was incomplete documentation as to which warnings were prepared ahead of time, and thus this case cannot be studied independently.

In contrast, there are several reasons for a long preparation time. On a number of occasions the forecast office had trouble with the software used to type the warnings. Also, increased detail in the warning text lengthens the preparation time. In some circumstances it is imperative that the warning be immediately transmitted, but in other cases a detailed warning is more appropriate. Thus in the latter situations, a longer preparation time seems justifiable.

3.8 Call for Ground Truth

After the issuing of a warning, the forecast office generally seeks ground truth reports. For this analysis, the SDS will be used because the SWATR are not needed. However, two episodes have incomplete action logs and therefore only 332 of the 351 warnings will be considered. It should also be noted that ham radio reports will be included with the phone calls as sources of ground truth reports. Finally, unless otherwise stated, both initiated and received calls are considered together. It is often difficult to separate the two because the WFO will not initiate a call if one has already been received. Figure 3.8 shows the number of calls to each of the warned counties.

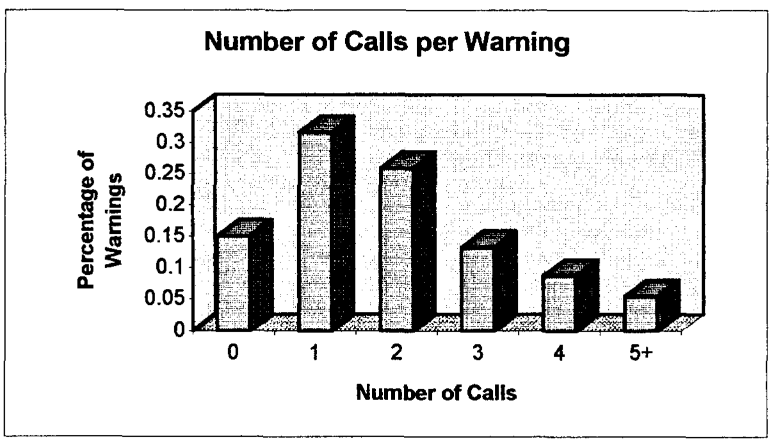


Figure 3.8. The Number of initiated and received calls per warning for the SDS excluding 19 warnings with incomplete Action Logs.

Notice that 58 percent of the warned counties are called once or twice but 15 percent are not called. There are several possible explanations for the cases where the

county was not called during the severe weather episode. First, during episodes with multiple valid warnings, it is difficult to keep track of all the warned counties. Secondly, there may have been calls that were never recorded on an Action Log. Again, this would be more likely to happen during an intense episode with many calls. Here, a report of conditions not meeting severe weather criteria could be lost.

3.9 Verify the Warning

Calls with ground truth reports are the only way the forecast office can receive real-time verification on a warning. A severe call is defined as a call that reports a severe local storm event. Figure 3.9 illustrates the times that severe calls occur.

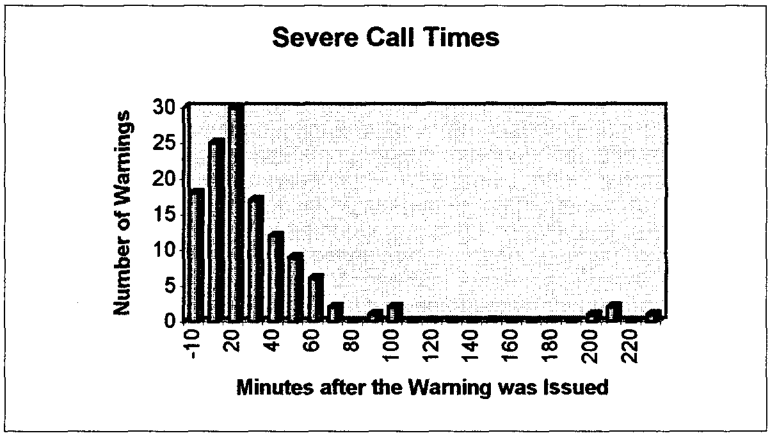


Figure 3.9. The time when episode verification is obtained in minutes after the warning is issued.

There are severe calls for 126 warnings which equates to 38 percent. Over 70 percent of the severe calls occur within 30 minutes after the warning is issued. The severe call was

initiated in 46 cases while it was received 68 times. However, it should be noted that of the 68 times the severe call was received, 33 of the counties had an initiated call prior to the received severe weather report.

Severe calls play a critical role in verifying warnings. There are three types of verification discussed in this research: real-time verification, episode verification and *Storm Data* verification. 'Real-time verification' is defined as apparent verification of a warning from a severe call during the valid warning period. Real-time verification aids the forecaster in the warning process by providing a current ground truth report indicating a cell is severe. 'Episode verification' encompasses real-time verification as well as any delayed severe calls received after the warning has expired but during the severe weather episode. A report that the weather was severe an hour ago during a valid warning period usually does not aid the forecaster in the warning process but may provide input to *Storm Data.* Finally, '*Storm Data* verification' is based on a *Storm Data* entry indicating that a severe local storm event occurred during the valid warning period as explained in chapter one. *Storm Data* verification will be described in detail in chapter four. For all three verification schemes, the verification rate is defined as the percentage of warnings that verify.

First, one could ask if taking time to investigate a cell increases the verification rate To answer this question, the real-time verification rate was analyzed for warnings with both an initiator and a trigger as well as for immediate trigger warnings for the PDS. Notice from Figure 3.1 that 47 warnings have both an initiator and a trigger. Of these 47 warnings, 25 had real-time verification equating to a 53 percent verification rate. Now

for immediate trigger warnings, 8 of 21 warnings had real-time verification equating to a 38 percent verification rate. However, using a contingency table analysis, warnings with both an initiator and a trigger do not have statistically higher verification rates than immediate trigger warnings.

Next, a comparison was made between the real-time verification rates for first and last warnings versus all other warnings. All the analysis for the remainder of this report is based on the SDS. The hypothesis was that first warnings would have lower verification rates because ground truth reports would not yet be available. A problem with this analysis is that the hypothesis should hold for the first warning on each cell, and during active episodes there are multiple cells. However, the best approximation available is the first warning during each severe weather episode. The real-time verification rate for first warnings was 0.27 as compared to 0.43 for all other warnings. Using a contingency table analysis, $X^2 = 5.208$, and therefore the verification rate is statistically significantly lower for first warnings.

Similarly, last warnings should have lower real-time verification rates because the forecast office might have difficulty determining when to stop warning for a cell. Again, this analysis should be done cell by cell but the best available approximation is the last warning in each episode. However, there was not a statistically significant difference in real-time verification rates between last warnings and all other warnings.

Since the national verification statistics are based on *Storm Data* verification, it is now important to compare episode verification to *Storm Data* verification as shown in

Table 3.7. Episode verification is used rather than real-time verification in order to assess the accuracy of severe calls.

Table 3.7. *Storm Data* and episode verification (defined in the text) are compared using a contingency table. The data set is the SDS excluding 19 warnings with missing Action Logs.

***Storm Data* Verification**

		Yes	No	Total
Episode Verification	Yes	88	38	126
	No	41	165	206
	Total	129	203	332

Looking at the first row, notice that 88 warnings had both types of verification while 38 warnings had episode but not *Storm Data* verification. This means that $\frac{88}{126}=.70$ of the warnings with episode verification appear in *Storm Data*. This can be equated to the accuracy of reports during the episode if *Storm Data* is accepted as the "truth". Another way consider this is that for 30 percent of the warnings with episode verification, the radar operator thinks he or she has verification on a warning while the reports are actually "false".

Now considering the second row, there are 41 warnings that have *Storm Data* verification but do not have episode verification. This equates to $\frac{41}{206}=.20$ of the warnings that the radar operator does not think have verified will have severe weather reports at a later time and become a part of *Storm Data*. Finally, there are 165 warnings

that do not have either *Storm Data* or episode verification which encompasses a 50 percent of the total warnings.

4. VERIFICATION RESULTS

Chapter three presented the importance of real time verification as a forecast tool as well as a comparison between episode and *Storm Data* verification. This chapter will focus on *Storm Data* verification by first presenting the past and present verification statistics and then providing a discussion of some of the factors affecting the statistics. Throughout this chapter, the SDS is used.

4.1 Verification Statistics

To put the RDU WFO verification statistics in perspective, the national statistics are first be presented in Fig. 4.1.

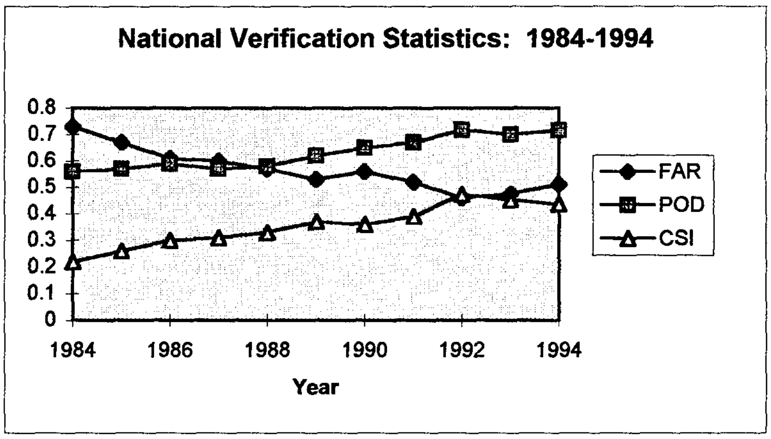


Figure 4.1. The national verification statistics from 1984 to 1994 (Crowther and Halmstad, 1995).

Notice the general improvement of the verification statistics over the ten year period. However, it can be seen that the FAR increases slightly over the last two years. However, Fig. 4.1 does not separate the stations with the WSR-88D from those that were still using

the conventional radar. The national verification statistics for stations with the WSR-88D from March 1, 1991 to June 30, 1995 are as follows: POD = 0.80, FAR = 0.45 and CSI = 0.48 (Burgess, 1996).

Now focusing on the local scale, Fig. 4.2 illustrates the verification statistics for the RDU WFO from 1984 to 1994. The explanation for the trends prior to this analysis period is unknown but clearly there was an increase in the FAR in 1988 and a corresponding decrease in the CSI. Also, the POD was low in 1991.

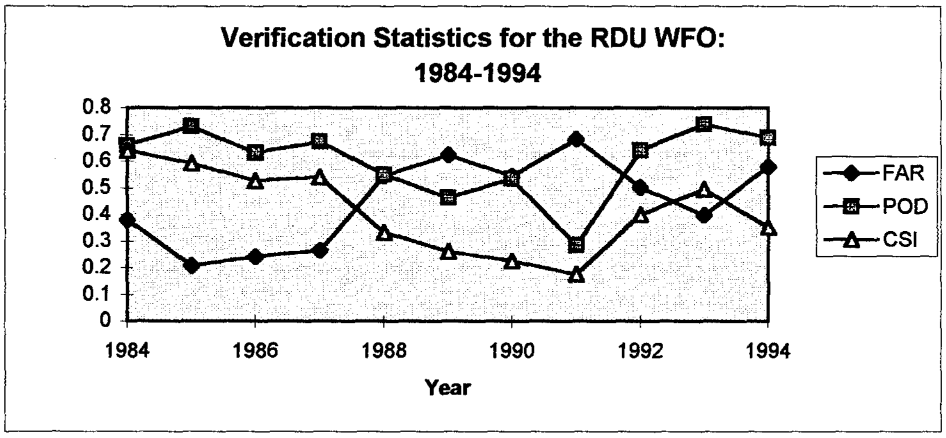


Figure 4.2. The verification statistics for the RDU WFO from 1984-1994 (Crowther and Halmstad, 1993-1995, Grenier and Halmstad, 1987 and 1991-1992, Grenier, Halmstad and Leftwich, 1988-1990, and Leftwich and Grenier, 1985-1986).

The above figure again does not indicate the warnings after the RDU WFO used the WSR-88D and therefore Table 4.1 is included. Notice that the table also separates the 1994 and 1995 statistics for the SDS.

Table 4.1. Verification statistics for the RDU WFO before and after the operational use of the WSR-88D. Note that the data set for pre WSR-88D is 1992-1993 and the post WSR-88D statistics are taken from the SDS. The last two columns are a breakdown of the SDS into the 1994 and 1995 warnings.

RDU WFO Verification Statistics:

	Pre WSR-88D (1992-1993)	Post WSR-88D (SDS)	1994 (SDS)	1995 (SDS)
Verified Warnings (X)	209	142	80	62
Misses (Y)	121	52	24	28
Unverified Warnings (Z)	166	209	64	145
Total Warnings Issued	375	351	144	207
POD	0.63	0.73	0.77	0.69
FAR	0.44	0.59	0.44	0.7
CSI	0.42	0.35	0.48	0.26

The next step is to examine the statistical contrasts between the periods using a Z test for the difference between two population proportions. The pre and post WSR-88D POD will be compared as an example of this test. A higher POD was hypothesized with the development of the WSR-88D and therefore a one tailed test will be used. The null and alternate hypotheses are:

H_o: $(POD_{post} - POD_{pre}) = 0$

H_A: $(POD_{post} - POD_{pre}) > 0$ (Mendenhall and Sincich, 1992).

The test statistic is: $$Z = \frac{POD_{post} - POD_{pre}}{\sqrt{\frac{X_{post}+X_{pre}}{n_{post}+n_{pre}}\left(1-\frac{X_{post}+X_{pre}}{n_{post}+n_{pre}}\right)\left(\frac{1}{n_{post}}+\frac{1}{n_{pre}}\right)}}$$

where $n_i = X_i + Y_i$, the denominator of the proportion being tested (Mendenhall and Sincich, 1992). The rejection region is $|Z| > Z_{crit}$ for a one tailed test. At the 0.05 confidence level, Z_{crit} is 1.645. This Z_{crit} will be used throughout the remainder of this paper unless otherwise specified. In this example, $Z = 2.32$ and hence H_o can be rejected.

Therefore, the POD is statistically significantly higher for the RDU WFO after the operational use of the WSR-88D began in March of 1994 over the previous two years.

The final step to completing the Z test is to verify that the sample is "sufficiently large". Some authors suggest looking at the following intervals :

$POD_i \pm 2\sqrt{\frac{POD_i(1-POD_i)}{n_i}}$ for both the pre and post WSR-88D periods (Mendenhall and Sincich, 1992). If neither interval contains zero or one, the sample is sufficiently large. For this example, the intervals are from 0.58 to 0.69 for the pre WSR-88D period and from 0.67 to 0.80 for the post WSR-88D sample. Because neither of these intervals contains zero or one, the assumption of a large sample is met. For the remainder of this chapter, unless otherwise stated, the assumption of a large sample has been met and will not be presented.

There are only two changes to the Z test for two tailed cases. First, for the above example the alternate hypothesis, H_A, would state that $(POD_{post} - POD_{pre}) \neq 0$. Secondly, and the rejection region at a confidence level of .05 has .025 in each tail and hence $Z_{crit} = \pm\ 1.96$.

Table 4.2. The resulting Z test statistics for the difference between two population proportions for the POD, FAR and CSI. The test was performed between Pre and Post WSR-88D periods and for the 1994 and 1995 SDS. The statistics and data sets are given in Table 4.1.

Z-Test Statistics			
	POD	FAR	CSI
Pre vs Post WSR-88D	-2.32	-4.12	2.11
1994 vs 1995	1.25	-4.81	4.4

Table 4.2 shows that H_o is also rejected for the FAR and CSI using either a one or two tailed test in the pre versus post WSR-88D comparison. However, from the data provided in table 4.1, it can thus be inferred that the FAR and CSI have gotten worse since the WSR-88D became operational at the RDU WFO. Looking at the 1994 versus 1995 comparison, H_o is not rejected for the POD but is rejected for the FAR and CSI. Again, it can be inferred that the FAR and the CSI have gotten worse.

For both the pre versus post WSR-88D comparison as well as the 1994 versus 1995 test, note that the increasing FAR drives the decreasing CSI. This is because the POD is increasing or remaining constant for the cases presented in this section, and the CSI is directly proportional to the POD. Thus only the rationale for the increasing FAR will be presented. Finally, it should be pointed out that there was also a slight increase in the national FAR from 1992 to 1994 as shown in Figure 4.1.

A hypothesis for the increasing FAR is that there is a tendency to over warn based on WSR-88D products. When operational use of the WSR-88D began in 1994, only a few radar operators at the RDU WFO had been trained on the Doppler radar . Therefore, each of the trained operators worked numerous severe weather episodes and gained a lot of warning experience during the 1994 severe weather season. However, many more forecasters were trained on the Doppler radar by the 1995 severe weather season. This meant that numerous radar operators were having their first operational WSR-88D experiences during the 1995 severe weather season. There is a steep learning curve for

the WSR-88D as discussed in section 1.4, and therefore the verification statistics could be expected to improve in future years if this hypothesis is true.

4.2 Factors Affecting Verification Statistics

The previous segment presented the verification statistics for the RDU WFO and this section will explore some of the factors affecting these verification statistics. Because the 1994 and 1995 FAR and CSI were shown to be statistically significantly different, these verification statistics for the two year groups will be examined separately when each category has a sufficiently large number of warnings. However, the POD may be examined for the entire SDS because there where not statistically significant differences found in the previous section.

4.2.1 Storm Environment

Clearly, the storm environment has an important impact on the verification statistics. However, there is not consistent documentation in the SWATR of the environment surrounding the severe weather episodes. For example, if the stability indices had been recorded for all the cases, episodes with similar indices could perhaps be grouped together and analyzed. However, even if such documentation were available, it is questionable whether or not the warnings would fall into clear categories. Therefore, two arbitrary breakdowns of the SDS have been made: (1) episodes with severe thunderstorm or tornado watches versus episodes without watches and (2) episodes with

more than four warnings (defined here as outbreaks) versus those with four or less warnings (non-outbreaks).

First, the watch versus no watch periods will be covered as summarized in the table 4.3.

Table 4.3. This table summarizes the verification statistics and Z-tests used in comparing watch and no watch periods. The Z test statistic is listed in the first column of the two categories being compared and bold numbers represent cases where H_o may be rejected.

Watch Versus No Watch Periods

	Watch	No Watch	1994: Watch	1994: No Watch	1995: Watch	1995: No Watch
Verified Warnings (X)	105	137	59	21	46	16
Misses (Y)	31	21	9	15	22	6
Unverified Warnings (Z)	140	69	43	21	97	48
Total Warnings Issued	245	106	102	42	143	64
POD	0.77	0.64	0.87	0.58	0.68	0.73
Z	**1.93**		**3.27**		-0.45	
FAR	0.57	0.65	0.42	0.50	0.68	0.75
Z	-1.39		-0.86		-1.05	
CSI	0.38	0.29	0.53	0.37	0.28	0.23
Z	**1.74**		**2.00**		0.80	

Notice that the POD is statistically significantly higher during watch periods than no watch periods. However, there are no differences in the FAR for any of the watch/no watch breakdowns. Finally, the CSI was higher for the 1994 warnings in the SDS during watches than no watch periods while there is no difference in the CSI for the 1995 period.

Secondly, outbreak versus non-outbreak periods will be compared as summarized in Table 4.4. The conclusions made for the previous watch/no watch analysis hold for the outbreak/non-outbreak comparison with the contrasts magnified.

Table 4.4. This table summarizes the verification statistics and Z-tests used in comparing outbreak and non-outbreak periods. The Z test statistic is listed in the first column of the two categories being compared and bold numbers represent cases where H_o may be rejected.

Outbreaks Versus Non-outbreaks

	Outbreaks	Non-Outbreaks	1994 Outbreaks	1994 Non-Outbreaks	1995 Outbreaks	1995 Non-Outbreaks
Verified Warnings (X)	115	27	68	8	47	11
Misses (Y)	24	28	6	18	18	10
Unverified Warnings (Z)	164	45	52	16	116	33
Total Warnings Issued	279	72	120	24	163	44
POD	0.83	0.49	0.91	0.30	0.72	0.52
Z	**4.77**		**6.28**		**1.69**	
FAR	0.59	0.63	0.43	0.67	0.71	0.75
Z	-0.57		**-2.09**		-0.50	
CSI	0.38	0.27	0.54	0.19	0.26	0.20
Z	**1.99**		**3.94**		0.84	

The POD is again statistically significantly higher for outbreaks than non-outbreaks. Notice the dramatic contrasts in the POD especially during 1994 with the outbreak category having 0.91 and only 0.30 for non-outbreaks. Further, the 1994 improvement is not at the expense of a higher false alarm rate. The FAR is in fact lower for 1994 outbreaks. Therefore, the CSI is also enhanced for 1994. There are no differences in the FAR and CSI between outbreak and non-outbreak periods for 1995.

The conclusion of a higher POD during watch periods and outbreaks is not a surprising result. Watch period and outbreaks are often associated with large storm systems. "Giant" storms generally have better verification statistics; during the JDOP there were many large storms, and hence the resulting verification statistics may have been too encouraging (Burgess, 1996).

4.2.2 The Verification Process

Obviously, the verification statistics are affected by the procedures used to derive them. This section will highlight two characteristics of the current national verification process: double jeopardy warning and warned counties.

First an example will be presented to illustrate the case of double jeopardy warnings. Suppose a *Storm Data* entry is recorded at 10:00, the warning was issued at 10:05 and no further *Storm Data* entries were made. Then both an unverified warning (Z) and a miss (Y) are recorded. The same holds true when the *Storm Data* entry appears after a warning expires. Both of these cases will be called 'double jeopardy' since two penalties are given.

In the SDS, there are 16 cases of double jeopardy. Half of these cases have the warning within ten minutes after the *Storm Data* entry while the remaining eight have the *Storm Data* entry within ten minutes after the warning expires. Assuming these double jeopardy cases verified and there was no miss, the POD and CSI increase by .02 and .04 respectively while the FAR decreases by .05. Clearly, crediting the forecast office with both a verified warning and no miss would allow the most enhancements in the

verification statistics, and yet the improvements are small. If either a verified warning or no miss were recorded, less significant enhancements in the verification statistics would be seen. Thus, double jeopardy warnings do not have a very significant effect on the verification statistics.

The second characteristic of the current warning process is that each warned county is verified independently. This means that when a warning was issued for two counties for the same cell, each county is verified independently. This circumstance when warnings are issued for more than one county be called multiple warnings. A reasonable hypothesis is that verification would only be received for one of the warned counties in the multiple warning case, and hence the verification rates would be lower for multiple warnings. For the SDS, the verification rate was .35 for multiple warnings versus .44 for individually warned counties. Using a contingency table, $X^2 = 3.215$ indicating that there is not a statistically significant difference in verification rates for the two classes of warnings.

4.2.3 Time of Day

The time of day impacts the number of warnings issued as well as the verification rate as shown in Fig. 4.3. Note that the verification rate is the only statistic analyzed here because the data set was too small to break up the misses (Y) into 6 categories. Also, the SDS has not been partitioned by year for this analysis because of the necessity of having a sufficiently large sample size.

It is not remarkable that there are more warnings issued in the late afternoon and evening hours. However, notice that the verification rate increases steadily throughout the day. Using a contingency table analysis, $X^2 = 17.13$ which is greater than $\chi^2_{crit} = 11.1$ with five degrees of freedom. Therefore, it can be concluded that the verification rate increases throughout the day. The conclusion to section 4.2.1 states that larger storms

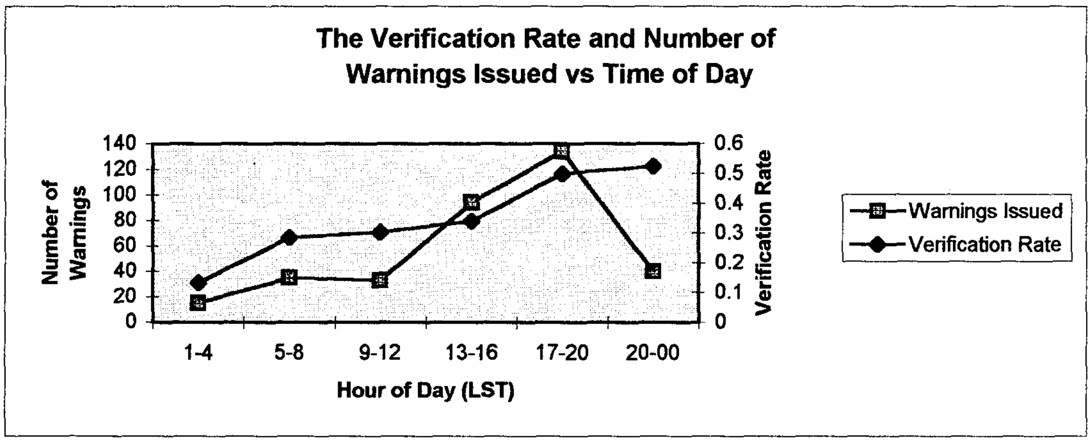


Figure 4.3. The number of warnings issued and the verification rate by the hour of the day. The SDS was used for this analysis.

have higher verification rates. Taking this rationale one step further, these large storms generally occur in the late afternoon and evening hours, and therefore the verification rate is higher during this period. Also, the verification rate is lowest during the night while most people are sleeping.

4.2.4 Population Density

According to Hales and Kelly (1985), national data from 1979 to 1985 showed that significantly more warnings were issued to highly populated regions. To see if this

trend was present in the SDS, regression models were used to determine the effects of population density on both the verification rate and the number of warnings issued. Both regression models were performed using SAS and the programs are included in appendix 7.4. Since warnings are issued by counties, this analysis uses the county population densities. This could cause errors because counties are not homogeneously populated.

The first model used a logistic regression to relate the verification rate, the dependent variable, to the population density, the independent variable. This is a special class of regression models where the dependent variable is bounded between zero and one and the errors have a binomial distribution (Hosmer and Lemeshow, 1989). The χ^2 distribution with one degree of freedom is used to determine if the independent variable is important to the model. In this example, $X^2 = 1.18$ which is not greater than χ^2_{crit}, and hence the population density does not have statistically significant impact on the model.

Because the population density did not have an important effect on the verification rate, the next step was to see if fewer warnings were issued to the sparsely populated counties because of the problems with verification. For this regression, the number of warnings was the dependent variable and the county area and population density were the independent variables. A Poisson regression was used because the dependent variable has the characteristics of a Poisson random variable:

1) The experiment involves counting the number of occurrences, i.e. the number of warnings issued, in a given unit of measurement, in this case the county.

2) The number of occurrences (warnings) for different counties are independent (Mendenhall and Sincich, 1992).

The X^2 values for this case were 15.30 for the counties area and 0.11 for the population density. Therefore, the county's area has a significant impact on the number of warnings issued with fewer warnings being issued to smaller counties. However, the population density did not have a statistically significant impact on the number of warnings issued. Because county area was a significant term in the model while population density was not, it is unlikely that the insignificant effect of population density is due to the sample being too small.

4.2.5 Per Capita Income

A similar analysis was conducted to determine the importance of the per capita income on the verification rate. A reasonable hypothesis was that a higher per capita income would indicate a higher education level and hence a greater awareness that the WFO should be contacted to report severe local storm events. The same two tests were conducted as described in the previous section. For the logistic regression, the verification rate was the dependent variable with the per capita income as the independent variable. The resulting X^2 was 3.27 which is not greater that χ^2_{crit} and hence the per capita income does not have a statistically significant impact on the verification rate. The second test conducted was a Poisson regression testing the impact of the population density and per capita income on the number of warnings issued. The resulting X^2 values were 0.047 and 1.65 for the population density and per capita income respectively. Thus, neither of the independent variables had a significant impact on the number of warnings issued.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Meteorologists first started forecasting severe thunderstorms and tornadoes in the nineteenth century and verification procedures were developed soon after. From the 1800's to the present, researchers have been trying to improve the severe weather forecast process. In recent years, the Doppler radar was developed in an attempt to increase severe weather warning timeliness and accuracy. This research has been a preliminary analysis of how warnings are issued using the WSR-88D at the RDU WFO.

The warning process was described in terms of the schematic representation of the warning process presented as Fig. 3.1. The initiators, triggers and decisions not to warn are categorized by either the radar products used or the ground truth reports received.

The radar operator starts by monitoring the situation throughout the county warning area. Then something happens, the initiator, which causes the radar operator to investigate a given cell and consider issuing a warning. There were no statistically significant conclusions as to which initiators occur most commonly. However, the initiator leads to the investigation of a suspicious cell. The average duration of this investigation is 7.2 minutes. Then, in thirty percent of the cases the decision is made not to issue the warning. Ground truth reports and reflectivity based products are equally important in these decisions not to warn while velocity based products are not as commonly used.

For the remaining seventy percent of the cases, the investigation leads to a trigger. A trigger is defined as that which drives the decision to issue the warning. The trigger

for severe thunderstorm warnings is usually reflectivity while for tornado warnings Doppler velocity products are most commonly used immediately prior to issuing the warning.

A subset of the warnings (31 percent) are immediate trigger warnings. These warnings had no initiator and investigation prior to the issuance of the waning. All immediate trigger warnings are severe thunderstorm warnings. There is a dramatic increase in the importance of ground truth reports for these immediate trigger cases.

The trigger leads to the issuance of the warning. Ground truth reports are then sought for 85 percent of the warnings to both to aid in the warning process as well as to gain verification on the warnings issued. This leads to the verification of 38 percent of the warnings during the severe weather episode. There is a 70 percent accuracy rate on calls reporting severe weather if *Storm Data* is used as the "truth".

Next, *Storm Data* verification was used to analyze the verification statistics. The POD at the RDU WFO has improved a statistically significant amount since operational use of the WSR-88D began in March of 1994. However, both the FAR and CSI have gotten worse with the Doppler radar. In the period with the WSR-88D, the POD has not changed between 1994 and 1995 but both the FAR and CSI have gotten worse. The POD is higher during periods with severe thunderstorm or tornado watches as well as for outbreaks. The verification rate increases throughout the day. Finally, the population density and per capita income do not affect either the verification rate or the number of warnings issued.

However, the reader is reminded of the discussion presented in section 1.2 concerning the problems with using verification statistics as a measure of warning accuracy. Are the majority of the severe local storm events that occur in the RWA reported? Recall that the OKC WFO's POD increased from .508 to .729 and the FAR decreased from .801 to .508 when intensive post storm surveys were initiated in 1983 as shown in Table 1.2. Would increased efforts at gaining ground truth reports have similar effects on the RDU WFO's verification statistics? As is expected elsewhere, the majority of the severe weather events at the RDU WFO are marginal severe local storm events such as dime size hail or wind gusts of just over 50 knots. Do such events merit a post storm survey? The emphasis should perhaps be focused on the warning process rather than the verification statistics.

This thesis serves as a preliminary examination of the warning process. Future research should provide more specific conclusions about the process. The SWAT recorder in the future will be able to determine the validity of the warning process presented in this report. The radar operators should also be encouraged to verbalize their thought process in order to increase the accuracy of the data. In addition, it would assist the documentation if the identification all radar products presented on the PUP were automatically recorded along with the time when presented. This would allow for a more detailed statistical analysis of the WSR-88D products used in conjunction with successful and unsuccessful warnings. A final recommendation would be to attempt to divide the warnings into categories in order to determine the products triggering the issuance of warnings for hail, straight line wind, etc. A detailed explanation of the spread sheet

organization is included in Appendix 7.2 to assist future researches. In addition, a computer disk containing all the files is available from Dr. Allen J. Riordan at NCSU.

6. LIST OF REFERENCES

Alberty, R. and Lt. Col. T. Crum, 1991: The NEXRAD Program: Past, Present, and Future; A 1991 Perspective. Preprints, *25th International Conf. on Radar Meteor*, AMS, Boston, 1-8.

Atlas, D., 1990: *Radar in Meteorology.* Amer. Meteor. Soc., Boston, 806 pp.

Auciello, E. and R. Lavoie, 1993: Collaborative Research Activities between National Weather Service Operational Offices and Universities. *Bull. Amer. Meteor. Soc.*, **74**, 625-629.

Burgess, D. and D. Devore, 1979: Doppler Radar Utility in Severe Weather Warning. Preprints, *11th Conf. on Severe Local Storms*, Kansas City, MO, Amer. Meteor. Soc., 577-579.

____________________, 1996: Doppler Radar: Then and Now. Keynote Address at the 18th Conference on Severe Local Storms on 18 Feb. 1996, San Francisco, CA, Amer. Meteor. Soc.,

Crowther, H. and J. Halmstad, 1993: *Severe Local Storm Warning Verification: 1992.* NOAA Technical Memorandum NWS NSSFC-37, 27 pp. (NTIS, PB93-227452)

___________ and _________, 1994: *Severe Local Storm Warning Verification: 1993.* NOAA Technical Memorandum NWS NSSFC-40, 38 pp. (NTIS, PB94-215811)

___________ and _________, 1995: *Severe Local Storm Warning Verification: 1994.* NOAA Technical Memorandum NWS NSSFC-41, 38 pp.

Daily Weather Maps: Weekly Series--Oct. 2-8, 1995. NOAA, NWS, NMC, Department of Commerce.

Flueck, J., 1987: A study of Some Measures of Forecast Verification. Preprints, *10th Conf. on Probability and Statistics in Atmospheric Science*, Edmonton, Alta, Canada, Amer. Meteor. Soc, 69-73.

Friday, E., 1994: The Modernization and Associated Restructuring of the National Weather Service: An Overview. *Bull. Amer. Meteor. Soc.*, **75**, 43-52.

Galway, J., 1985: J. P. Finley: The First Severe Storms Forecaster. *Bull. Amer. Meteor. Soc.*, **66**, 1389-1395.

Grenier, L. and J. Halmstad, 1986: *Severe Local Storm Warning Verification Preliminary Procedures*, NOAA Technical Memorandum NWS NSSFC-12, 10 pp. (NTIS, PB86-194362)

_________ and _________, 1987: *Severe Local Storm Warning Verification: 1986*, NOAA Technical Memorandum NWS NSSFC-17, 19 pp. (NTIS, PB87-195939)

_________ and _________, 1991: *Severe Local Storm Warning Verification: 1990*, NOAA Technical Memorandum NWS NSSFC-30, 32 pp. (NTIS, PB91-227520)

_________ and _________, 1992: *Severe Local Storm Warning Verification: 1991*, NOAA Technical Memorandum NWS NSSFC-33, 28 pp. (NTIS, PB92-185982/AS)

_________, _________, and P. W. Leftwich: 1988: *Severe Local Storm Warning Verification: 1987*. NOAA Technical Memorandum NWS NSSFC-20, 14 pp. (NTIS, PB88-241393)

_________, _________, and __________: 1989: *Severe Local Storm Warning Verification: 1988*. NOAA Technical Memorandum NWS NSSFC-23, 26 pp. (NTIS, PB89-226310/AS)

_________, _________, and __________: 1990: *Severe Local Storm Warning Verification: 1989*. NOAA Technical Memorandum NWS NSSFC-27, 25 pp. (NTIS, PB90-248592)

Hales, J. and D. Kelly, 1985: The Relationship Between the Collection of Severe Thunderstorm Reports and Warning Verification. Preprints, *14th Conf. on Severe Local Storms*, Indianapolis, IN, Amer. Meteor. Soc., 13-16.

_______, 1988: Improving the Watch/Warning Program Through use of Significant Event Data. Preprints, *15th Conf. on Severe Local Storms*, Baltimore, MD, Amer. Meteor. Soc., 165-168.

Hosmer and Lemeshow, 1989: *Applied Logistic Regression*. John Wiley and Sons, New York, 307 pp.

Hughes, P., 1970: *A Century of Weather Service: A History of the Birth and Growth of the National Weather Service--1870-1970*. Gordon and Breach, Science Publishers, Inc, New York, 212 pp.

Klazura, G. and D. Imy, 1993: A Description of the Initial Set of Analysis Products Available from the NEXRAD WSR-88D System. *Bull. Amer. Meteor. Soc*, **74**, 1293-1311.

Leftwich, P. W. and L. A. Grenier, 1985: *Severe Local Storm Warning Verification: 1984.* NOAA Technical Memorandum NWS NSSFC-10, 14 pp. (NTIS, PB86-148244)

___________ and ___________, 1986: *Severe Local Storm Warning Verification: 1985.* NOAA Technical Memorandum NWS NSSFC-14, 16 pp. (NTIS, PB87-137147/AS)

Lemon, L., E. Quoetone, and L. Ruthi, 1992: WSR-88D: Effective Operational Applications of a High Data Rate. Preprints, *Symposium on Weather Forecasting*, AMS, Boston, 173-180.

Lemons, G., 1995: Press ready North Carolina Storm Data Entries. RDU WFO.

McCullagh, P. and J. A. Nelder, 1989: *Generalized Linear Models: Second Edition.* Chapman and Hall, New York, 511 pp.

Mendenhall, W. and T. Sincich, 1992: *Statistics for Engineering and the Sciences.* Dellen Publishing Company, San Francisco, 963 pp.

Polger, P., B. Goldsmith, R. Przywarty, and J. Bocchieri, 1994: National Weather Service Warning Performance Based on the WSR-88D. *Bull. Amer. Meteor. Soc.*, **75**, 203-214.

Schaefer, J., 1990: The Critical Success Index as an Indicator of Warning Skill. *Weather and Forecasting*, **5**, 570-575.

Staff of JDOP, 1979: Final Report on Joint Doppler Operational Project (JDOP) 1976-78. NSSL Tech. Memo. ERL NSSL-86, Norman, Nat'l. Severe Storm Lab., 84 pp. (NTIS, PB80-107188/AS)

Storm Data: A composite of Outstanding Storms--July, 1994. Vol. 36, No. 7. NOAA, Nat'l Envir. Satellite Data and Inform. Service, and Nat'l Climatic Data Center, NC.

Storm Data: A composite of Outstanding Storms--August, 1994. Vol. 36, No. 8. NOAA, Nat'l Envir. Satellite Data and Inform. Service, and Nat'l Climatic Data Center, NC.

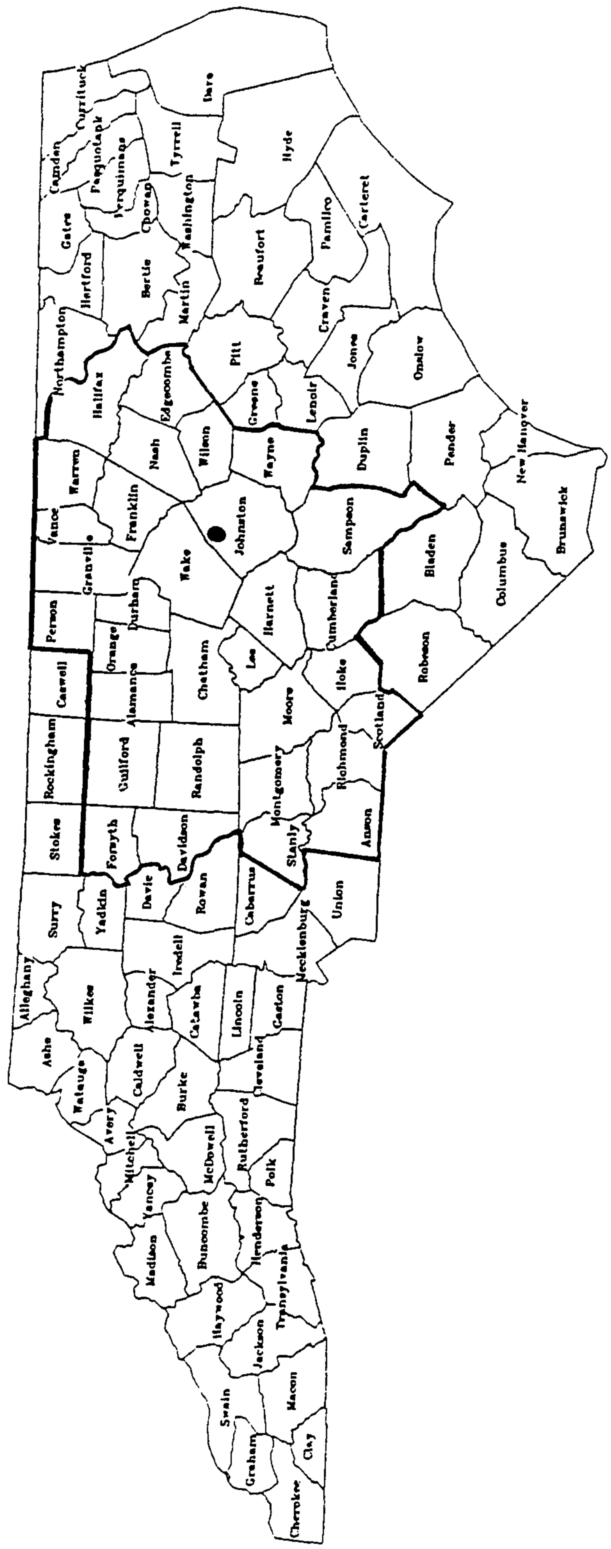
The Tornado Project. 1994: Tornado Video Classics: The Ultimate Tornado Experience.

United States Census Bureau. *1990 Densus of Population and Housing.*

Whitnah, D. R., 1961: *A History of the United States Weather Bureau.* Univ. of Illinois Press, Urbana, Ill. 267 pp.

7. APPENDICES

7.1 Map of the Raleigh Warning Area (RWA)



The interior of the bold enclosure is the RWA. The dot in Johnston County near the Wake County line indicates the position of the WSR-88D in Clayton, NC.

7.2 SPREADSHEET ORGANIZATION

The data has been organized into five different types of spreadsheets: the Episode Summaries, the Master Warning List, the Warning Process Spreadsheet, the Decisions Not to Warn, and the List of Misses. The purpose for each spreadsheet will be briefly discussed followed by a detailed explanation of each column entry. Because of the excessive length, the spreadsheets have not been included in this report and are available to future researchers on disk from Dr. Allen J. Riordan in the Department of Marine Earth and Atmospheric Science at NCSU. However, the spreadsheets used in this thesis are by no means the best manner in which to handle the data, and subsequent researchers are encouraged to devise their own organization method.

7.2.1 Event Summaries

The Episode Summaries compile the information from the Warning Logs, Action Logs, call records form the SWATR, and *Storm Data* by episode in a timeline fashion for the ESDS. This phase in the data organization process is simply meant to put the warning and call information together in an usable manner for building the remaining spreadsheets. The column entries are as follows:

A) The time in Eastern Daylight Time (EDT) (or Eastern Standard Time (EST) if applicable) using a 24 hour clock.

B) The county where the documented activity occurred.

C) The location within the county (N, S, etc.). This designation is only used for warnings issued for a portion of the county.

CALLS

D and E) Initiated and received calls are classified by category. 'SVR' and 'TOR' categories signify calls that meet severe thunderstorm or tornado criteria respectively. Similarly, 'Not SVR' and 'Not TOR' represent calls that fail to meet severe thunderstorm or tornado standards as defined in chapter one. Calls from both the Action Logs and the SWATR are included. The time recorded in the Action Log is used except for the case explained for column F. Most calls listed in the SWATR are also in the Action Logs but occasionally a call was never entered in the Action Log. There may be errors in the analysis of ground truth reports because of missing calls in the Action Log.

F) The time of the event is recorded only if documented in the Action Logs or the SWATR. For other cases, the only information known about the time of the event is that it occurred prior to the call. Unfortunately, the Action Log entries are occasionally listed by event time rather than call time. For these cases, if the SWATR list a call time, the SWATR time is listed in column A and the Action Log event time is placed in column F. However, SWATR are not available for all episodes and their focus is not to list all call information. There may be cases when the Action Log lists event times and there is not a SWAT Report available to correct these times to the call times. If the event time is listed as a call time, the radar operator is assumed to know of the report and be able to use the information in the decision making process.

G) The source of the call information is recorded in this column where 'A' represents the Action Logs, 'S' stands for the SWATR, and 'B' is for both the Action Log and the SWAT Report.

WARNINGS

H) All severe thunderstorm (SVR) and tornado (TOR) warning are listed. Also MISS is listed for misses as defined in chapter one.

I) The time the warning expires--EDT or EST using a 24 hour clock.

J) The warning number during the given severe weather episode. For cases where more than one county was warned, all counties are listed with the same warning number.

K) For warning verification, a Yes or No is listed in column 11 for warnings that do and do not verify respectively.

L) Additional information explaining entries is provided in this column. Examples of entries would be a call time discrepancy between the Action Logs and the SWATR. Column L also gives the specific information about how warnings verified: winds, hail (size), or a tornado.

7.2.2 Master Warning List

The Master Warning List is a spreadsheet with 351 rows composed of the warning in the ESDS and 45 columns containing information about the warning. General episode data is included such as the date, total number of warnings, watch information, and if the SWAT was present. The remainder of the spreadsheet is composed of specific

warning information. First, the time, location, warning number in the episode, type of warning and specific verification information are provided. Then a number of columns list variables that could affect verification including: if the episode was an outbreak, if the warning was issued during sleeping hours of 2300-0700, if multiple counties were simultaneously warned, and if the warning was a double jeopardy warning. Lastly, initiated and received call information is listed for before, during and after the warning was issued. Next, each column entry will be explained. Note that the columns that answer questions will be either in binary (0 meaning no and 1 meaning yes) or have Y and N representing yes and no respectively.

A-C) The warning date, year and time (EDT or EST).

D) Was the SWAT present during the warning?

E) Was the SWAT present at any point during the severe weather episode?

F) The hour of the day. For example, a warning at 16:18 would have a 16 in this column.

G) The county warned. Note that each warned county is listed separately for this spreadsheet.

H) The type of warning issued--SVR for severe thunderstorm and TOR for tornado.

I) The warning number during the severe weather episode. For example, the third warning of the episode would have a three. The warning number is by cell and not by individual warned counties. In other words if both Wake and Durham Counties were warned simultaneously, both warnings would have the same

warning number. Adjacent counties warned simultaneously are assumed to be for the same cell.

J) Were warnings issued to multiple adjacent counties simultaneously?

K) Was only a portion of the county warned (N, S, etc.)?

L) Was the warning issued between 07:00 and 23:00?

M) Were more than four warnings issued during the severe weather episode? In other words, was the episode an outbreak?

N) Was there a valid severe thunderstorm or tornado watch for anywhere in the Raleigh Warning Area?

O) Did the warning verify?

P-R) Did the warning verify with a report of thunderstorm winds, hail or a tornado?

S) Was the warning a case of double jeopardy?

T) The time difference between when the warning was issued (or expired) and the time of the storm data entry in ten minute increments for double jeopardy cases. For example, a 10 means that the warning expired within ten minutes of the storm data entry. Negative times indicate that the warning was issued after the storm data entry time.

U) Were multiple adjacent counties simultaneously warned?

V) The total number of telephone calls (initiated or received) and ham radio reports were recorded from the warned county.

W) The total number of severe thunderstorm or tornado reports (from initiated or received telephone calls or ham radio reports) were recorded from the warned county.

X) The total number of received telephone calls or ham radio reports reporting severe thunderstorms or tornadoes.

Y) The total number of initiated telephone calls reporting severe thunderstorms or tornadoes.

Z) The time when the first severe thunderstorm or tornado report is received via an initiated or received telephone call or a ham radio report.

AA) Was the first severe weather report initiated or received?

AB) Was there an initiated call prior to the report of severe weather? If the first severe weather report was initiated, the answer is yes.

AC-AG) This section concerns calls prior to when the county was warned. Column AC gives the total number of calls prior to the issuance of the warning and the subsequent columns indicate the total number of initiated severe weather reports (AD), initiated reports of conditions not meeting severe weather criteria (AE), received severe weather reports (AF), and received reports of conditions not meeting severe weather criteria (AG).

AH-AL) This section concerns calls during the valid warning period and is presented in a parallel manner to the previous section.

AM-AQ) This section concerns calls after the warning has expired and is presented in a parallel manner to the previous two sections.

AR) The total number of initiated and received calls during the severe weather episode to the warned county. In cases where the county was warned more than once, the calls are separated between the two warnings. There is normally a logical split. In cases where the warning was upgraded from a severe thunderstorm to a tornado warning and both warnings are valid, the calls are recorded for both warnings.

AS) The total number of warnings during the severe weather episode.

7.2.3 The Warning Process Spreadsheet

The Warning Process Spreadsheet again lists the warnings by rows with details concerning the warning in columns. However, information concerning the warning triggers and tracks through the warning process are also included, and therefore this spreadsheet only covers the CPDS. The two warning triggers are listed with the categories listed in Table 3.1. The following columns are included in the Warning Process Spreadsheet:

A-C) The date, type of warning issued and the county warned. Note that for multiple adjacent warned counties, all counties are listed together in column C.

D) Were multiple adjacent counties warned?

E) The time the warning was issued in EDT or EST.

F) The warning number during the severe weather episode. Note that multiple simultaneously warned counties all get the same warning number.

G) The total number of cells with warnings issued during the episode. In other words, multiple warned counties still are only treated as a single warning.

H) A detailed account of the initiator. All information from the SWATR is included in this column.

I) The categories of initiator(s) are listed. Note that this column includes all initiators.

J) The initiator-simplified lists only the first event causing the radar operator to focus his or her attention on the individual county and consider issuing a warning for that county.

K) The time between the initiator and the trigger.

L-N) These columns are the same as H-J except covering the trigger. Note that the last event prior to the issuance of the warning is used in column N.

O) Was previous verification of a warning a trigger for the issuance of the warning?

P) Did the warning have real time verification?

Q) The amount of time between the decision to issue the warning and the official warning time.

R) Was the county called after the warning was issued?

S) Did the warning verify via storm data?

T) Any additional information that needs to be noted should be included in the discussion section.

7.2.4 Decisions Not to Issue Warnings

Documented decisions not to issue warning were recorded from the SWATR for the episodes in the CPDS. The are 24 decisions not to issue a warning are listed in a similar manner to the Warning Process Spreadsheet.

A-D) The date, type, time and county involved. Similar to the Warning Process Spreadsheet, if the operator decides not to warn several counties on the same cell, there is only one listed decision not to warn.

E) Was the decision not to extend an existing warning?

F-H) The same as H-J under the Warning Process Spreadsheet.

I) The trigger(s) for the decision not to issue the warning.

J) The categories of triggers for the decisions not to warn.

K) The last category of activity prior to the decision not to issue the warning.

L) Was the decision not to warn correct using storm data as the verification source?

7.2.5 List of Misses

The list of misses is a record of the 52 storm data entries that were not during warnings for the ESDS. This spreadsheet is a parallel version to the Master Warning Spreadsheet without warning specific information.

A-C) The date, time and county of the miss.

D-F) Was the missed event hail, wind or a tornado?

G) For hail misses, was the hail less than one inch in diameter?

H) Was there a severe thunderstorm or tornado watch?

I) Was there a severe call at the time of the storm data entry?

J-K) If there was a call associated with the storm data entry, was it initiated or received?

L) Were more than four warnings issued during the severe weather episode containing the miss?

7.3 Spreadsheet Excerpts

7.3.1 Example of an Event Summary

12 June 1995											
Severe Thunderstorm Watch											
Radar Operator: Delgado											
Radar Recorder: Riordan (16:41-19:10)											
Hail, Wind & Tornado Events											
			CALLS				WARNINGS				NOTES
Time	County		Initiated	Received	Time	R,A	Type	Until	#	Verifies?	
(EDT)					of event	B,*					
16:17	Randolph		Not SVR			A					
16:23	Scotland		Not SVR			A					
16:27	Granville		Not SVR			A					
16:35	Scotland			Not SVR		A					
16:40	Scotland		Not SVR			A					
16:42	Vance		Not SVR			A					
16:43	Chatham		Not SVR			A					
16:48	Anson		Not SVR			A					
16:48	Stanley						SVR	17:15	1	NO	
16:48	Stanly		Not SVR			A					
16:52	Harnett		Not SVR			B*					R=16:54
16:52	Vance	N					SVR	17:30	2	NO	
16:55	Granville		Not SVR			A					
16:55	Vance		Not SVR			A					
16:58	Cumber.		Not SVR			B*					R=16:54
17:02	Cumber.		Not SVR			B					
17:03	Scotland			Not SVR		A					
17:08	Granville		Not SVR			B*					R=17:02
17:08	Hoke						SVR	17:45	3	YES	Hail (.75)
17:08	Hoke		Not SVR			A					
17:12	Orange			Not SVR		B*					R=17:16
17:12	Stanly		Not SVR			B*					R=17:11
17:12	Vance		Not SVR			B*					R=17:09
17:14	Johnston		Not SVR			A					
17:15	Harnett		Not SVR			A					
17:16	Wake		Not SVR			A					
17:17	Person		Not SVR			B					R=17:16
17:18	Hoke			SVR		B*					R=17:14
17:18	Vance			Not SVR		A					
17:20	Chatham		Not SVR			A					
17:20	Harnett		Not SVR			B*					R=17:24
17:22	Scotland		Not SVR			B*					R=17:21

17:23	Harnett						SVR	18:15	4	NO	
17:25	Harnett		Not SVR			B*					R=17:24
17:30	Cumber.		Not SVR			A					
17:33	Cumber.			SVR		B*					R=17:31
17:34	Johnston		Not SVR			A					
17:36	Cumber.			SVR		A					
17:36	Johnston						SVR	18:15	5	NO	
17:36	Sampson	N					SVR	18:15	5	YES	Hail (1.0)
17:39	Cumber.						SVR	18:15	6	YES	Hail (1.5)
17:40	Warren		Not SVR			A					
17:41	Wake		Not SVR			B*					R=17:38
17:41	Wake			Not SVR		R					
17:42	Wake	E					SVR	18:15	7	YES	Hail (1.5)
17:43	Wake		Not SVR			B*					R=17:41
17:50	Sampson			Not SVR		B*					R=17:48
17:50	Wayne		Not SVR			A					
17:52	Wake		Not SVR			A					
17:58	Wayne	W					SVR	18:30	8	NO	
18:00	Johnston			Not SVR		A					
18:00	Sampson			Not SVR		B*					R=17:58
18:00	Wayne		Not SVR			A					
18:05	Moore		Not SVR			A					
18:07	Wake			Not SVR		A					
18:10	Wake		Not SVR			A					
18:23	Wayne		Not SVR			B*					R=18:22
18:27	Halifax		Not SVR			B*					R=18:29
18:30	Harnett						MISS				Wind
18:33	Halifax		Not SVR			B*					R=18:31
18:36	Franklin		Not SVR			A					
18:36	Wayne		Not SVR			B					
18:37	Wayne		SVR			R					
18:40	Halifax			Not SVR		A					
18:40	Wayne	E					SVR	19:15	9	NO	
18:42	Cumber.		Not SVR			A					
18:43	Lee		Not SVR			B					
18:44	Cumber.		Not SVR			A					
18:45	Wake		Not SVR			A					
18:50	Franklin		Not SVR			B					R=18:47
18:50	Lee			Not SVR		R					
18:50	Sampson		Not SVR			A					
19:03	Halifax		Not SVR			B*					R=19:00
19:13	Halifax						MISS				F1 Tornado
19:13	Halifax		Not SVR			B*					R=19:10
19:14	Halifax						TOR	19:45	10	NO	
19:16	Halifax		Not SVR			A					
19:35	Hoke		Not SVR			A					

7.3.2 Excerpt from the Warning Process Spreadsheet

The Warning Process

Date	Type	County	Time	Initator(s)	Investi-gation time	Trigger(s)	Verify: Real Time	Prep Time	Verify: Storm Data
8-Mar	TOR	Chatham, Durham	14:44	The vertical reflectivity structure shows 65 dBZ at 17 kft and 50 dBZ to 25	10	A mesocyclone is detected in the region.	N0	4	NO
8-Mar	TOR	Granville	15:29	A new mesocyclone develops	10	The reflectivity is 65 dBZ with vault and pendant	YES	N	YES
1-May	SVR	Stanly	22:34	None	N/A	There is a report of golf ball size hail in Cabarrus Co. and the cell is entering	NO	2	NO
1-May	TOR	Anson	23:12	The warned Union Co. cell is moving into Anson Co. as seen on the reflectivity.	21	There is a report of golf ball size hail & "minor" tornado damage in Union Co.	YES	3	YES
10-May	TOR	Forsyth	20:09	There is a call reporting funnel cloud in the area of a 50 dBZ cell with a VIL of	5	The cell has a shear of +10 to -10 kts	NO	3	NO
10-May	SVR	Guilford	20:35	There is a call reporting a funnel cloud near a 50 dBZ reflectivity core.	3	The VIL is 45.	NO	6	NO
13-May	SVR	Scotland	19:42	None	N/A	The previous warning verified with both dime size hail and trees down. The cell moving into Scotland	YES	2	YES
13-May	SVR	Anson	20:18	A cross section of reflectivity shows 50 dBZ extending to 20 kft.	3	The VIL is 45.	YES	3	NO

15-May	SVR	Moore	16:04	None	N/A	The reflectivity cross section shows an elevated core of 55 dBZ. The VIL is 60. A second reflectivity cross section shows 65 dBZ at 18 kft.	YES	2	YES
15-May	SVR	Sampson	16:17	None	N/A	The verified Harnett Co. cell is moving into Sampson Co.	YES	2	NO
15-May	SVR	Hoke	16:32	A cross-section of reflectivity shows 50 to 55 dBZ at 10 to 20 kft.	3	The Moore Co. Warning verified and the cell is now entering Hoke Co.	NO	2	NO
15-May	TOR	Sampson	16:39	The cross-section shows a 65 dBZ core at 18 kft which is leaning strongly. The velocity field shows a small area of 30 kt. gate to gate shear.	5	The cross-section shows the 65 dBZ core has risen to 20 kft and there is now 55 dBZ to 40 kft. A region of 35 kt shear is collocated with the 65 dBZ core.	YES	1	YES
15-May	SVR	Sampson	17:25	None	N/A	A cell has fired up along an outflow boundary with a max reflectivity of 65 dBZ--There is currently a tornado warning for Sampson so waiting until it expires to issue a severe thunderstorm warning on this cell.	NO	1	NO
17-May	SVR	Johnston	17:18	Analysis of the velocity field in the region of a Meso Alert shows a good meso signature at mid-levels suggesting a moderate mesocyclone	5	There is wind shear at 14 kft of 35-40 kts. This is not gate to gate shear, but involves a well-organized pattern of pixels. The max reflectivity has increased to 65 dBZ.	NO	2	NO

19-May	SVR	Durham, Wake	8:19	The VIL is now 40 in northern Chatham Co. A 3D-correlated shear alert sounded for NE Chatham Co. near the Durham Co. line.	7	The maximum reflectivity is 55 dBZ near the Chatham Co. line. Ground truth reports are requested but warned without any.	NO	1	NO
19-May	SVR	Scotland	9:22	None	N/A	There is a severe thunderstorm report from Richmond Co. and Scotland Co. is next in the cell's path.	YES	1	NO
19-May	TOR	Hoke	9:33	There is a report of hail, strong winds and a funnel cloud in NE Scotland--near the Hoke Co.	2	The radar's mesocyclone alert sounds very near the previous ground truth report.	YES	1	YES
19-May	SVR	Cumber.	9:49	None	N/A	The Hoke Co. warning verifies with a report of trees down. The radar operator checks numerous products showing the cell is remaining the same intensity as it approaches Cumberland Co.	NO	2	NO
19-May	SVR	Johnston, Sampson	10:07	There is an alert for 3-D correlated shear in northeast Cumberland Co. The cell is approaching Sampson and S. Johnston Counties.	6	The VIL has increased from 45 to 55 near the Sampson Co. line.	YES	1	NO
19-May	SVR	Sampson, Wayne	10:21	None	N/A	The previously verified storm cell maintaining intensity and entering Wayne Co.	YES	2	NO
19-May	TOR	Wayne	10:28	There is a current verified severe thunderstorm warning for Wayne Co. and the intensity of the cell is continued to be monitored.	5	There is a report of a tornado in Sampson Co.	YES	2	NO

19-May	SVR	Stanly	14:39	VIL of 45 which is above the "VIL of the day" of 40 as determined by Charlotte's warning area. Charlotte is called to discuss the cell in Cabarrus Co.	7	A cross-section shows a large vertical extent of the storm.	YES	1	NO
19-May	SVR	Montgom.	15:02	There is a ground truth report of pea size hail in Stanly Co. and the cell is moving into Montgomery Co. The warning is prepared but the operator would like some confirmation on Stanly Co. damage before issuing it.	5	There are reflectivity values of 65 dBZ and a VIL of 52. The warning is edited to include the eastern half of Montgomery Co.	YES	1	YES
19-May	SVR	Moore	15:30	The Montgomery Co. warning has verified and the cell is progressing into	20	3D Correlated Shear is present in the cell.	YES	1	YES
19-May	SVR	Hoke,	15:55	Reflectivity Values have increased to over 70 dBZ in Moore Co. There are reports of marble size hail associated with these cells.	8	There is a report of golf ball size hail in Moore Co. verifying the previous warning- Hoke Co. is next in cells track.	NO	1	NO
19-May	SVR	Johnston	16:45	There is a report of winds greater than 60 kts and small hail at Fort Bragg. The cell is moving into Johnston Co.	20	The wet-bulb zero is used to determine that the storms in Western Johnston Co. are strong enough to produce large hail.	NO	1	NO
26-May	SVR	Franklin, Nash	16:55	There is an alert for 3-D correlated shear in NE Franklin Co.	8	There is a report of large hail in Franklin Co. which has not been warned.	NO	4	NO

9-Jun	SVR	Wake, Franklin	20:41	There is a mesocyclone alert in SE Vance County. Some rotation present on the 4 panel velocity product. 36 to 50 kt. winds are indicated from Vance to Franklin Co. Calling Franklin Co. for reports.	35	A VIL of 60 is reported in South Franklin and Northern Wake Counties.	NO	3	NO
9-Jun	SVR	Johnston	20:56	Johnston Co. is in the track of previously warned cells that have reports of high winds and funnel clouds. Johnston Co. is in a cone of silence.	5	There is a call with pea size hail in Johnston Co.	NO	2	NO
11-Jun	SVR	Franklin	18:29	Several cells in Franklin Co. have a VIL of 35+.	2	A X-section has an elevated core. The composite reflectivity shows an intense cell in SW Franklin Co. and the shape concerns the operator.	YES	5	YES
11-Jun	SVR	Sampson	19:59	A 60 mph wind was reported in Sampson Co.	3	The composite reflectivity has a max of 71 dBZ. The base velocity maximums are -41 and 49 kts.	YES	1	YES
12-Jun	SVR	Stanley	16:48	None	N/A	There is a call from the Charlotte NWS about their Union Co. warning. The cell is now entering Stanly Co. and has a reflectivity of 65 dBZ.	NO	3	NO

12-Jun	SVR	Vance	16:52	None	N/A	A large cell is in NW Vance Co. with reflectivity values of 55 to 60 dBZ. A cross section of this cell shows a max core of 65 dBZ with good southward overhang.	NO	3	NO
12-Jun	SVR	Hoke	17:08	None	N/A	The reflectivity is 65 dBZ in western Hoke Co.	YES	3	YES
12-Jun	SVR	Harnett	17:23	There is a report of 3/4 inch hail in Hoke Co. verifying last warning and the cell is tracking to the NW.	5	There is an initiated a call to Harnett Co. for reports. A cross section shows 50 dBZ extending to about 20,000 ft. The core is around 55 dBZ and shows some overhang.	NO	4	NO
12-Jun	SVR	Johnston, Sampson	17:36	There is a Meso Alert in NW Sampson County. The 4-panel storm relative velocity shows that the meso is in well developed. It is located on the south side of the reflectivity echo.	3	A report is received of dime size hail in Fayetteville (Cumberland Co).	NO	4	NO
12-Jun	SVR	Wake	17:42	None	N/A	Radar operator noted a strong area of return in SE Wake Co and requested that a call be initiated to get ground truth reports. No reports were received prior to preparing the warning but a large hail report was received before it was issued.	NO	3	YES

12-Jun	SVR	Wayne	17:58	A warning is prepared ahead of time based on a cross section in western Wayne Co.	12	Another Cross Section shows a 65 dBZ core at 18 kft. The core is narrow, but shows a strong overhang.	YES	3	NO
12-Jun	SVR	Wayne	18:40	None	N/A	Seymour-Johnson AFB reports 58 mph winds and 1/2" hail verifying the previous warning and prompting consideration of extending the warning. A cross section of this cell shows a core of 55 dBZ at 12 to 22 kft with a 3 nmi tilt.	NO	2	NO
16-Jun	SVR	Forsyth, W	15:08	Hail is reported in Forsyth Co and the warning is prepared ahead of time. The report was pea size hail and waiting on intensification of the cell.	5	The VIL has increased to 55+ in NW Forsyth Co.	YES	N	NO
16-Jun	SVR	Forsyth, NE	15:18	VIL of 55 on Blacksburgs radar in NE Forsyth Co. The warning is prepared and	3	The base reflectivity is 60+ dBZ and the decision is made to issue the warning.	YES	N	NO
16-Jun	SVR	Forsyth	15:52	None	N/A	A report of dime size hail verifies the previous warnings and prompts the consideration of extending them. A cross section of the cell shows a core of 55 dBZ to 30 kft.	NO	N	NO
16-Jun	SVR	Guilford	16:26	None	N/A	X-section shows the cell has pulsed up. The core of 55 dBZ extends to 28 kft with 50 dBZ to 33 kft. The VIL is 50+ in this cell.	NO	2	NO

21-Jul	SVR	Hoke, Scotland	16:40	None	N/A	VIL increasing rapidly in the area, storm moving to the right (eastward) more rapidly than other cells.	NO	1	NO
21-Jul	SVR	Richmond	16:52	None	N/A	VIL of 65 and the algorithm indicates hail positive	NO	1	NO
5-Oct	TOR	Cumber.	8:11	There is gate to gate shear of over 35 kts in the cell over Cumberland Co. Initiated a call to Cumberland Co.	?	Report of a tornado in NE Roberson Co.	NO	1	NO
5-Oct	TOR	Chatham	8:37	The relative velocity over Chatham Co. indicates gate to gate shear of 26 kts at 7700 ft.	7	The new volume scan shows 35 kts. gate to gate shear at mid levels in a 50 to 55 dBZ cell in central Chatham Co.	YES	1	NO
5-Oct	TOR	Orange	8:51	There is a report of trees down verifying the Chatham Co. warning and the cell tracking toward SW Orange Co.	10	Gate to gate shear of 25 kts is present in SW Orange Co.	NO	1	NO
5-Oct	TOR	Wayne	9:51	The relative velocity shows weak rotation in Sampson Co.	8	There is a Meso Alert and 31 kts shear over 1.3mi. in Sampson Co. A call to Sampson Co. yields a report of trees down in Sampson Co.	NO	1	YES
5-Oct	TOR	Johnston	9:51	The relative velocity shows weak rotation in Sampson Co.	8	There is a Meso Alert and 31 kts shear over 1.3mi. in Sampson Co. A call to Sampson Co. yields a report of trees down in Sampson Co.	NO	1	YES

5-Oct	TOR	Harnett	17:20	The Meso Alert sounds for the south side of a cell on the Lee-Harnett Co. line.	6	3-D correlated Shear is present on the same cell in the next volume scan.	NO	1	NO
5-Oct	TOR	Chatham	17:20	The Meso Alert sounds for the south side of a cell on the Lee-Harnett Co. line.	6	3-D correlated Shear is present on the same cell in the next volume scan.	NO	1	NO
5-Oct	TOR	Wake	17:20	The Meso Alert sounds for the south side of a cell on the Lee-Harnett Co. line.	6	3-D correlated Shear is present on the same cell in the next volume scan.	YES	1	NO
5-Oct	TOR	Wake	17:49	The relative velocity indicates shear of 30 kts over 1/2 mile for a cell in SW	11	A tornado is reported near the Shearon Harris Power Plant (SW Wake).	YES	5	NO
5-Oct	SVR	Johnston	18:48	There was a report of trees down in Garner in the last few minutes	3	The composite reflectivity shows bowing in eastern Wake Co.	NO	2	NO
5-Oct	SVR	Wake	18:48	There was a report of trees down in Garner in the last few minutes	3	The composite reflectivity shows bowing in eastern Wake Co.	YES	2	NO
27-Oct	SVR	Orange	18:11	The operator is considering issuing a warning for Orange Co. which is in the track of a mesocyclone.	8	The radar operator would like to look at a slice of the SRM but the radar is not storing these products. The decision is made to go ahead based on a single level of SRM.	YES	6	YES
27-Oct	SVR	Durham	18:29	Significant shear shown on the storm relative motion.	3	There is an Alert for a Storm Eye in Durham Co.	NO	N	YES
27-Oct	SVR	Granville	18:47	There is an Alert: Hail Positive in Granville Co.	7	Significant shear is present in Durham Co. The region of high composite reflectivity is moving into Granville Co.	YES	2	YES

27-Oct	TOR	Granville	19:08	The relative velocity show over 40 kts. gate to gate shear. The SRM products are not available.	3	The base velocity shows 44 kts. shear in 4 miles.	YES	4	YES
27-Oct	TOR	Vance	19:18	Vance Co. is in the path of the previous tornado warning but the radar operator is holding off on receiving a ground truth report.	3	There is a report of a small tornado in Granville Co. A Mesocyclone is present on the Vance/Granville Co. line.	YES	2	YES
27-Oct	TOR	Warren	19:47	The cell is moving into Warren Co. and a report is received of trees down and an overturned trailer in Vance Co.	4	There is a 40 kt. gate to gate shear over 1 mile.	YES	N	YES
27-Oct	TOR	Vance	19:57	There is a Mesocyclone Alert in western Vance Co.	2	The composite reflectivity still shows the mesocyclone and 60 dBZ in Vance Co.	YES	2	NO
11-Nov	SVR	Warren	18:48	None	N/A	Verification of previous warnings	NO	1	
11-Nov	SVR	Wayne, Wilson	18:59	None	N/A	Verification of previous warnings	NO	1	
11-Nov	SVR	Halifax, Nash	18:59	None	N/A	Verification of previous warnings	YES	1	
11-Nov	SVR	Edgec	19:30	None	N/A	Verification of previous warnings	YES	1	
11-Nov	SVR	Halifax	19:40	None	N/A	Verification of previous warnings and the line is slowing down as shown on the composite reflectivity.	NO	1	

7.3.3 Excerpt from the Decisions Not to Issue Warnings

Decisions Not to Warn

Date	Type	Time	County	Initiator(s)	Decision Not to warn	Verify
15-May	SVR	16:03	Hoke	The radar operator is considering issuing a warning for Moore Co. based on the cross section and now debates as to whether to include Hoke Co. as well.	The cell has slowed down and the operate decides to reassess in 30 minutes.	No
15-May	SVR	16:14	Harnett	The verified Harnett Co. warning is about to expire and the cross section is indicating an elevated 55 to 60 dBZ core that is leaning south. The max reflectivity is 65 dBZ near the surface.	The cell is exiting the county so the decision is made not to extend the warning.	Yes
19-May	SVR	17:15	Hoke, Cumberland, Wake	The Hoke Co. Cell is starting to bow.	There have been no ground truth reports on the cells	Yes
19-May	TOR	14:56	Randolph	There is a report of a funnel cloud in Radolph Co.	The echo does not show any cyclonic shear in Randolph Co.	Yes
19-May	SVR	8:02	Lee	The warned Chatham Co. cell is approaching the Lee Co. boarder.	There has only been a funnel cloud report in Chatham Co.	Yes
19-May	SVR	8:03	Warren	There are reflectivity echoes bowing into SW Warren Co.	There have not been any ground truth reports with this cell.	Yes
19-May	SVR	8:31	Franklin, Nash	A warning is considered but no specific trigger one is given.	The cells are losing organization and the VILs are low.	Yes
19-May	SVR	10:50	Sampson	The radar operator is considering extending the Sampson Co. warning but no specific information is given	The cell in Sampson Co. is losing strength--its maximum reflectivity is down to 30 dBZ and the cross section is not impressive.	Yes
26-May	SVR	17:49	Nash	The radar operator is considering extending the warning based on a report of marble size hail and the reflectivity is 66 dBZ on the cell.	The cross section does not look impressive and there have not been any reports of hail larger than marble size.	Yes

26-May	SVR	16:36	Warren	The cell has a maximum reflectivity of 66 dBZ	The operator decided not to warn until getting verification on the cell	Yes
11-Jun	SVR	18:03	Wake, Harnett	There are patches of 55 dBZ and a report of a funnel cloud.	The cross section is skinny and unimpressive.	No
12-Jun	SVR	16:57	Granville	It is documented that the warning was prepared but it is unclear what the trigger was.	The VIL has decreased and there have been no reports of severe weather.	Yes
12-Jun	SVR	18:14	Harnett, Johnston, Sampson, Cumber.	A review of all the warnings due to expire at 18:15 promted the consideration of extending the warnings.	The VILs are down to only 30 or 40 and the operator decides to let all the warnings expire as scheduled at 18:15.	No
12-Jun	SVR	18:53	Lee	There is a report of "light hail" in Lee Co.	The cross section shows good tilt but the core top is only 10 kft.	Yes
16-Jun	SVR	16:42	Forsyth/ N. Davidson	The VIL is 45+ and the cross section shows 55 dBZ to 17 kft.	The operator decides not to warn because there hasn't been verification on previous warnings.	Yes
16-Jun	SVR	17:00	Guilford	The radar operator is considering extending warnings based on a report of	The VIL is steady at 40 and the operator decides not to warn.	Yes
16-Jun	SVR	15:55	Forsyth	The cell on the Davie/Forsyth Co. boarder has pulsed back up.	The cross section only has a core of 50 dBZ to 24 kft.	Yes
5-Oct	SVR	19:32	Nash	The radar operator is looking at the composite reflectivity when the decision is made to prepare a warning for Nash Co.	The operator decided not to warn Nash Co. because of a report that they were only receiving rain.	Yes
5-Oct	TOR	18:04	Franklin	There have been funnel cloud sightings in NE Wake Co. and a tornado warning is prepared for Franklin Co.	There are skywarn spotters in the area and yet there have not been any reports of severe weather.	Yes
5-Oct	TOR	9:05	Harnett, Cumber.	Harnett and Cumberland Co. are next in the cells track.	The operator decides to stop warning because of a lack of verification on the cell.	Yes
5-Oct	SVR	7:41	Cumber.	There is a 26 kt. gate to gate shear.	There has been a lack of verification on the cell.	Yes
27-Oct	SVR	20:37	Davidson	The VIL is 45 and the operator thinks that a warning would be justified.	There are no people in this area and it will be impossible to get	Yes

27-Oct	TOR	19:30	Durham	The relative velocity shows significant shear and the cross section has a small section of 65 dBZ.	This cell is not as strong as others today and the operator decides not to warn.	Yes
11-Nov	SVR	19:11	Franklin	The radar operator is monitoring the composite reflectivity and notices that the cell has slowed down substantially.	The cell is in the eastern half of the county and the operator decides to just let the warning expire.	?

7.4 SAS Data and Program

Data for analysis of affects of population density and per capita income on verification rate.

County	Warnings	Verified Warnings	Percent Verified	Population Density (km^{-2})*	County Area (km^2)*	Per Capita Income (dollars)
Chatham	13	4	0.31	21.90	1837	19787
Cumberland	12	7	0.58	162.30	1706	16403
Durham	11	2	0.18	241.60	772	21547
Edgecombe	10	4	0.40	43.20	1312	15432
Franklin	18	7	0.39	28.60	1280	14858
Granville	19	7	0.37	27.90	1390	15191
Halifax	8	2	0.25	29.50	1893	14587
Harnett	14	7	0.50	44.00	1557	14525
Hoke	9	3	0.33	22.60	1016	11921
Johnst	22	11	0.50	39.60	2061	17450
Lee	5	2	0.40	62.10	672	19699
Moore	17	10	0.59	32.60	1829	21458
Nash	10	3	0.30	54.80	1406	18704
Orange	10	4	0.40	90.60	1039	21945
Person	8	4	0.50	29.70	1047	16849
Scotland	6	2	0.33	40.80	831	15352
Vance	9	4	0.44	59.20	699	15726
Wake	18	13	0.72	196.00	2221	23959
Warren	5	1	0.20	15.50	1150	11989
Wayne	17	7	0.41	73.10	1442	15261
Wilson	12	7	0.58	68.70	969	18596

SAS Program

```
Data a;
infile 'data.txt' dlm='09'x dsd;

*Variable Definitions:  warn  = the number of warning issued to each county
*                       verif  = the number of warnings that verify to each county
*                       pop  = the population density of the county per square km
*                       area  = the area of the county in square km
*                       income  = the per caita income for each county in dollars

input warn verif pop area income;

*Do logistic regression to see if the verification rate is a function of the population
*density.
proc genmod;
model verif/warn=pop  /expected type1 type3 dist = binomial link=logit;

*Do logistic regression to see if the verification rate is a function of the per capita
*income
proc genmod;
model verif/warn=income  /expected type1 type3 dist = binomial link=logit;

*Do Poisson regression to see if the number of warnings issued is a function of either the
*county's area or the popultion density.
proc genmod;
make 'obstats' out=pred;
model warn = area pop /obstats expected type1 type3 dist = poisson;

*Do Poisson regression to see if the number of warnings issued is a function of either the
*population density or the per capita income.
Proc genmod;
make 'obstats' out=pred;
model warn = pop income/obstats expected type1 type3 dist = poisson;

run;
```